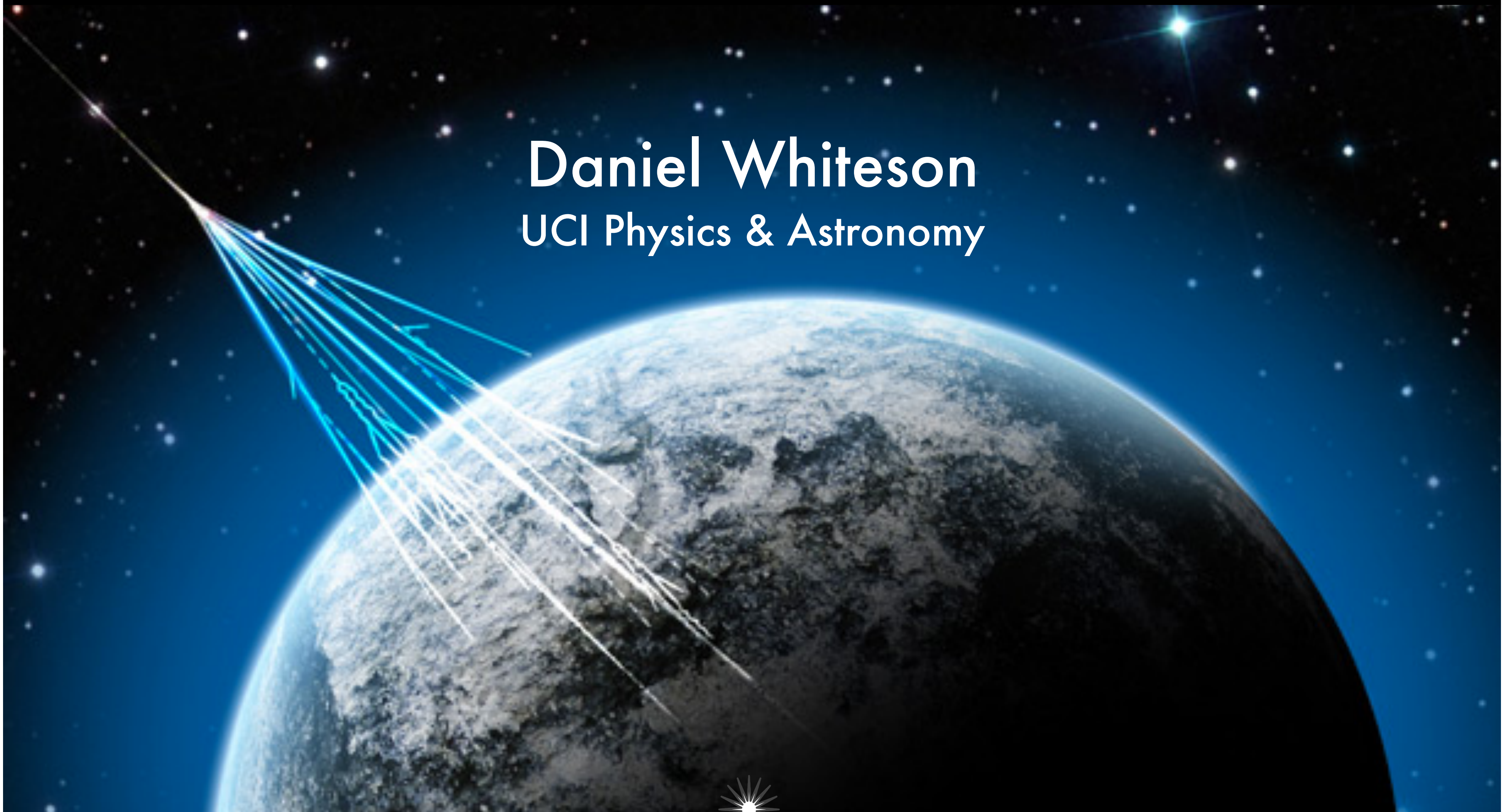
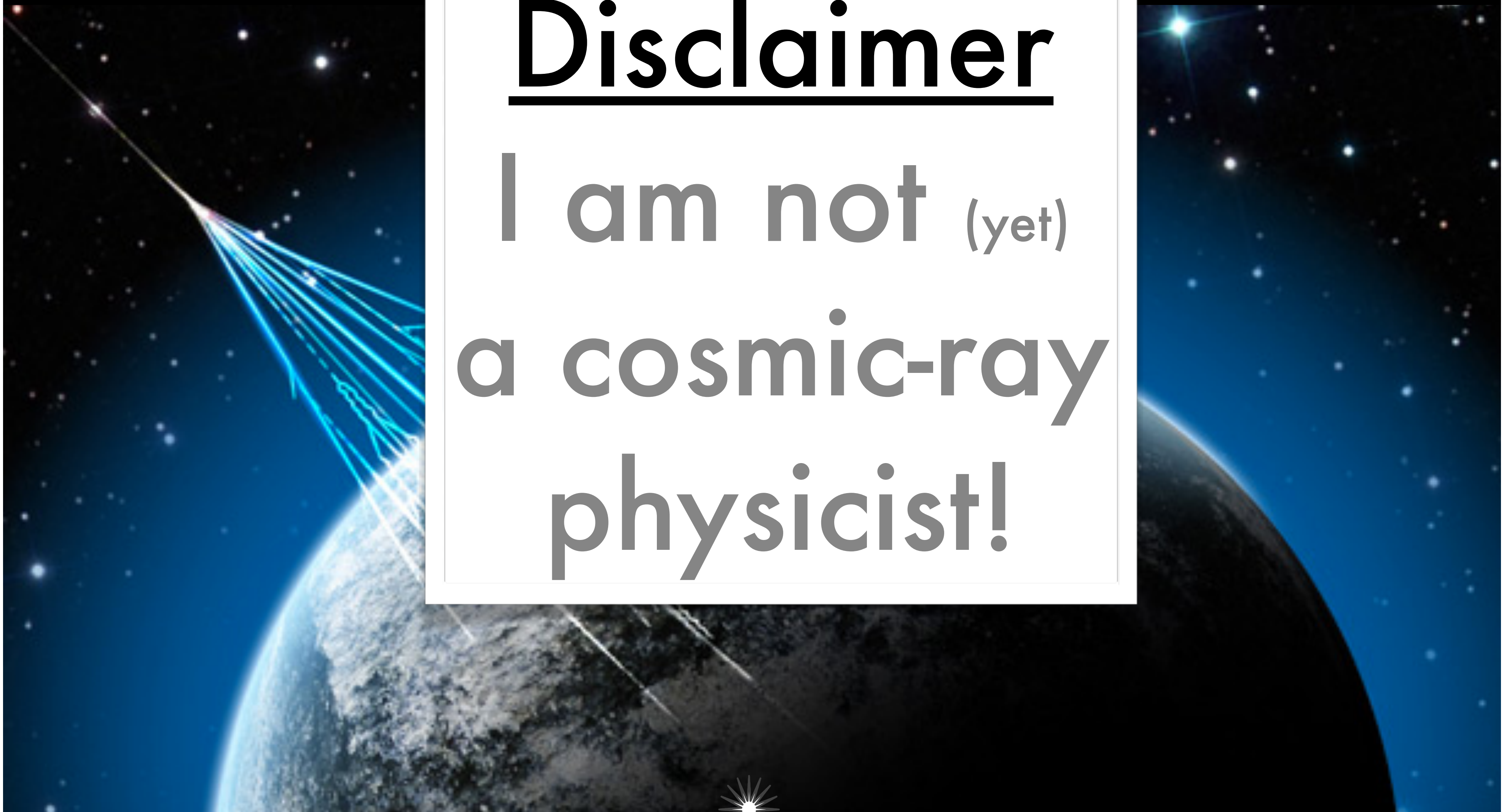
Cosmic Rays in Your Pocket



Daniel Whiteson
UCI Physics & Astronomy

CRAYFIS
cosmic rays found in smartphones

Cosmic Rays in Your Pocket



Disclaimer

I am not (yet) a cosmic-ray physicist!

CRAYFIS

cosmic rays found in smartphones

nature COMMUNICATIONS

ARTICLE

Received 19 Feb 2014 | Accepted 4 Jun 2014 | Published 2 Jul 2014

DOI: 10.1038/ncomms5308

Searching for exotic particles in high-energy physics with deep learning

P. Baldi[1], P. Sadowski[1] & D. Whiteson[2]

Bounds on Invisible Higgs boson Decays from $t\bar{t}H$ Production

Ning Zhou,[1] Zepyoor Khechadoorian,[1] Daniel Whiteson,[1] and Tim M.P. Tait[1]
[1]Department of Physics and Astronomy, University of California, Irvine, CA 92697

Disentangling Instrumental Features of the 130 GeV Fermi Line

Daniel Whiteson[1]

Mono-Higgs: a new collider probe of dark matter

Linda Carpenter,[1] Anthony DiFranzo,[2] Michael Mulhearn,[3] Chase Shimmin,[2] Sean Tulin,[4] and Daniel Whiteson[2]

Search for dark matter in events with a Z boson and missing transverse momentu pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

(Dated: July 8, 2014)

Search for Dark Matter in Events with a Hadronically Decaying W or Z Boson and Missing Transverse Momentum in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

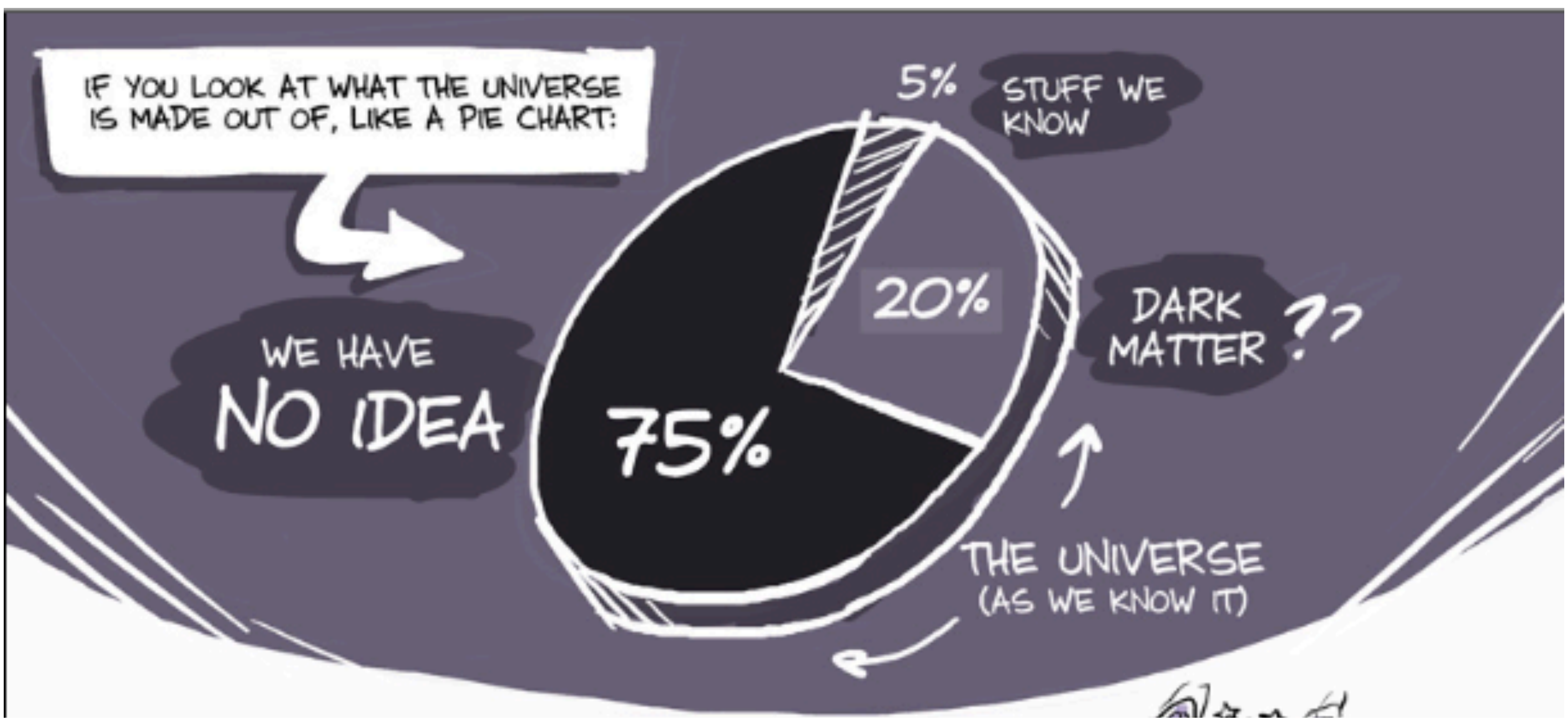
G. Aad *et al.**
(ATLAS Collaboration)

Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration
(Dated: February 3, 2015)

But....

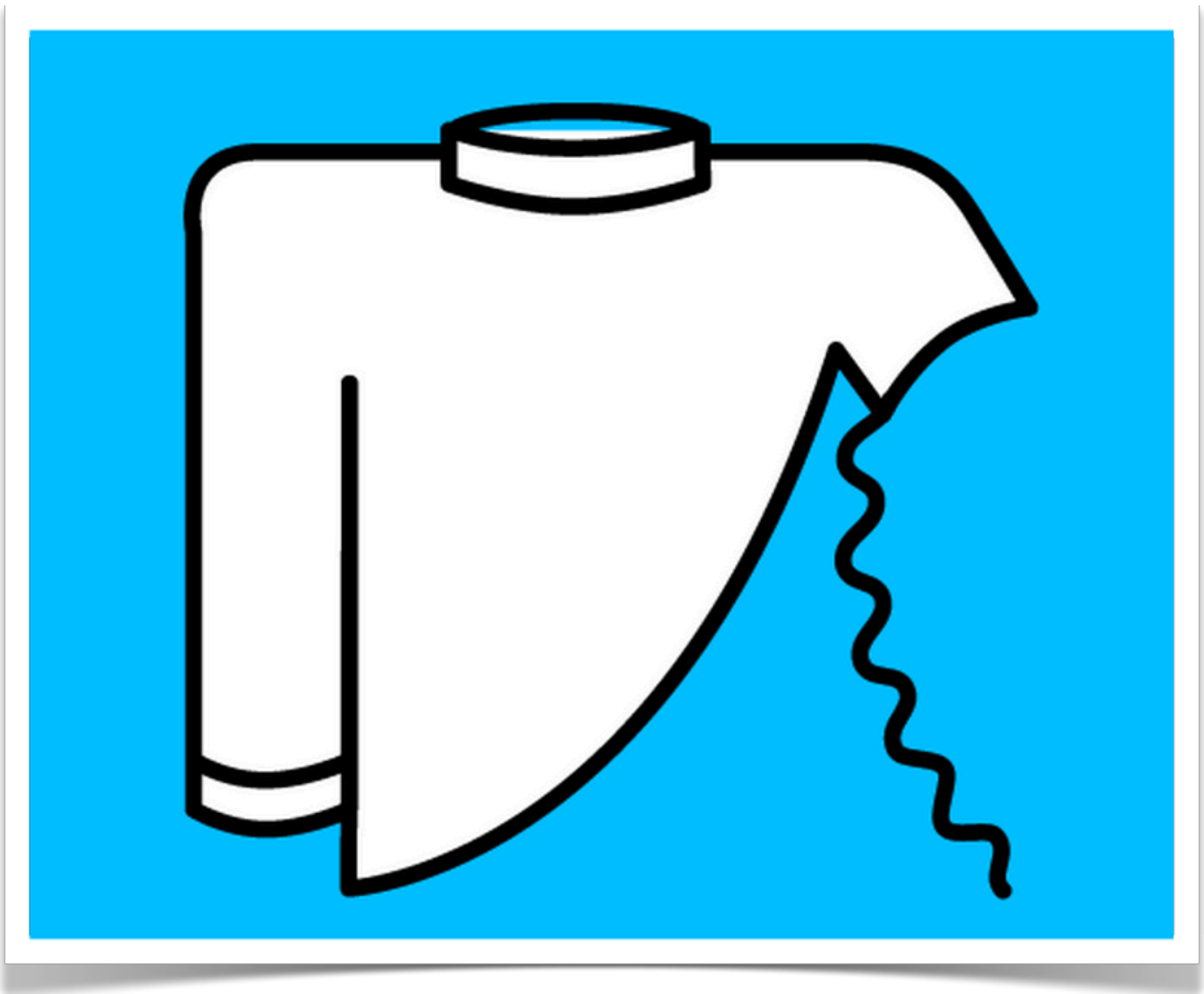
I am interested in how little
we understand the Universe around us



Perspective

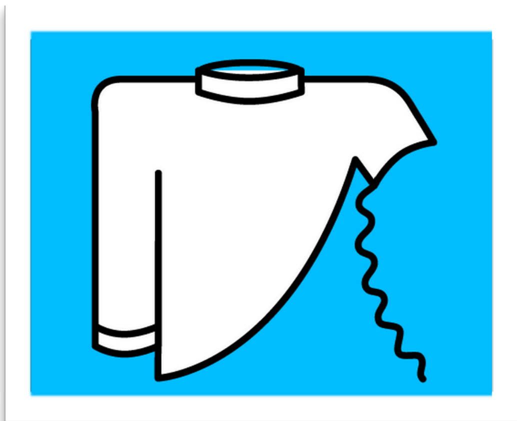
It's certainly true that major discoveries await us

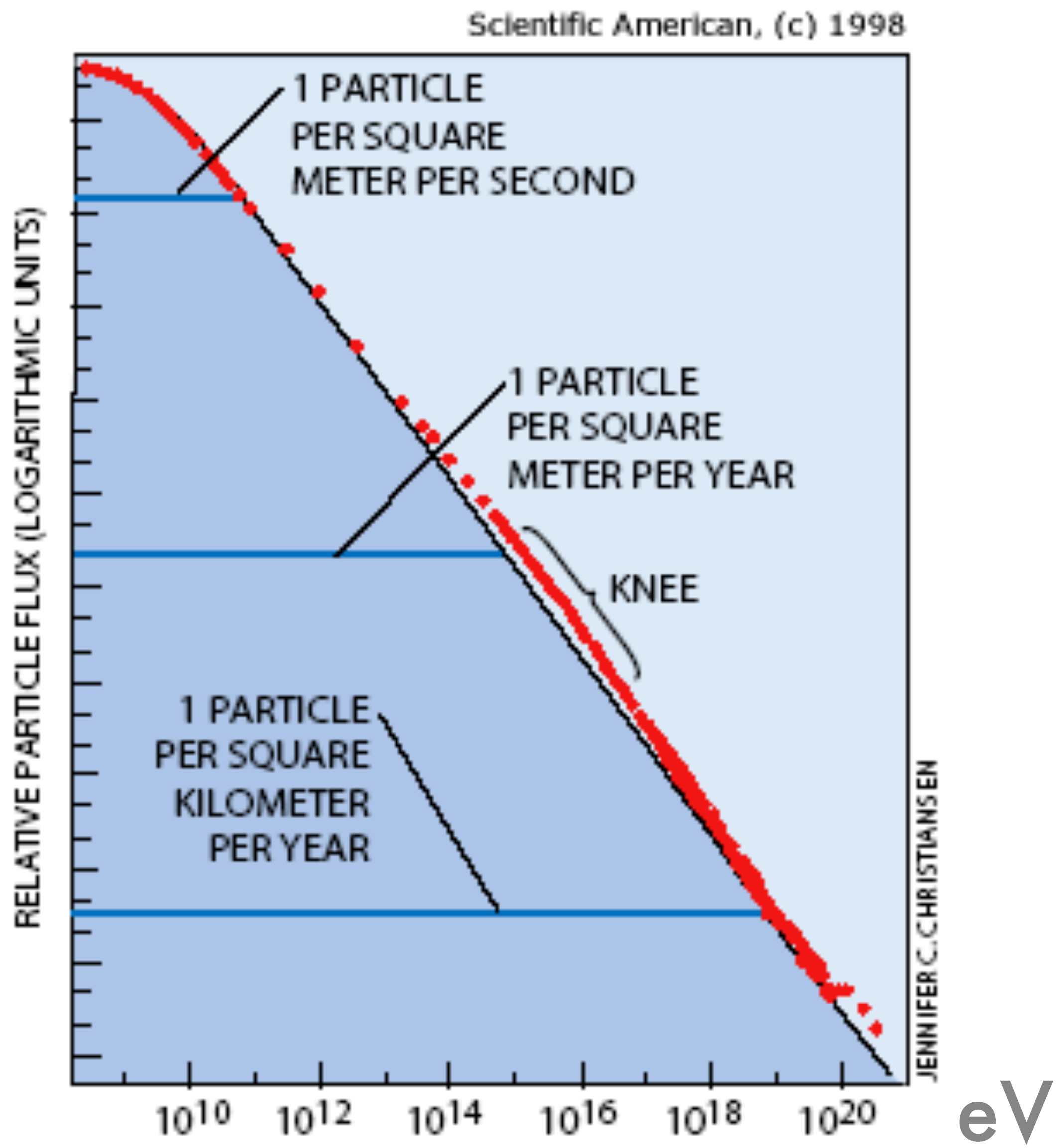
Loose threads



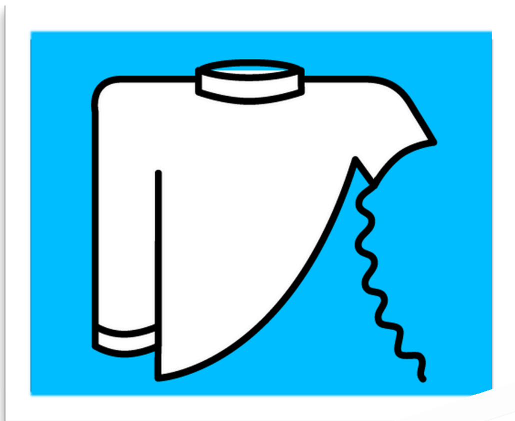
Pull on them as hard as you can!

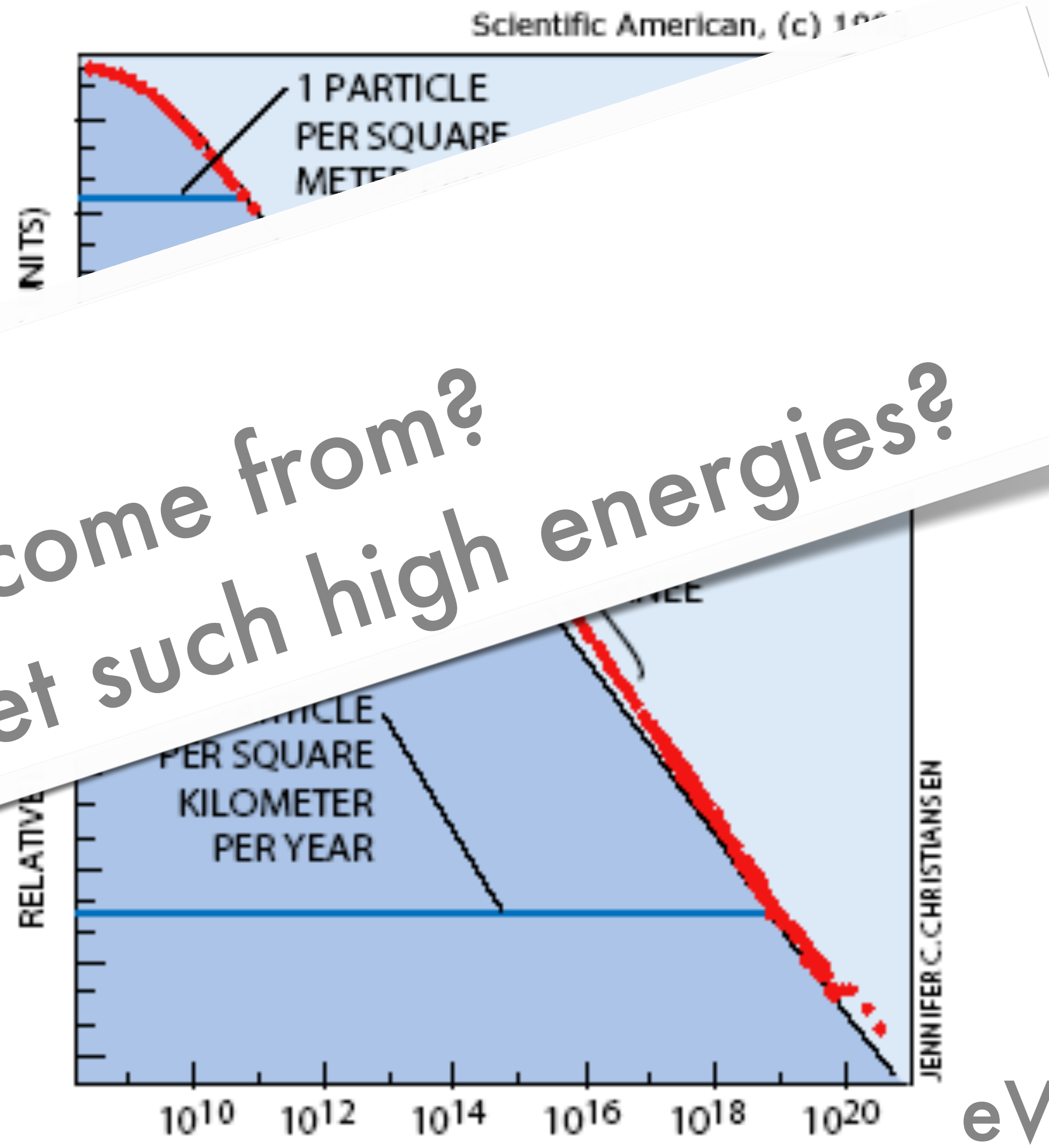
A loose thread





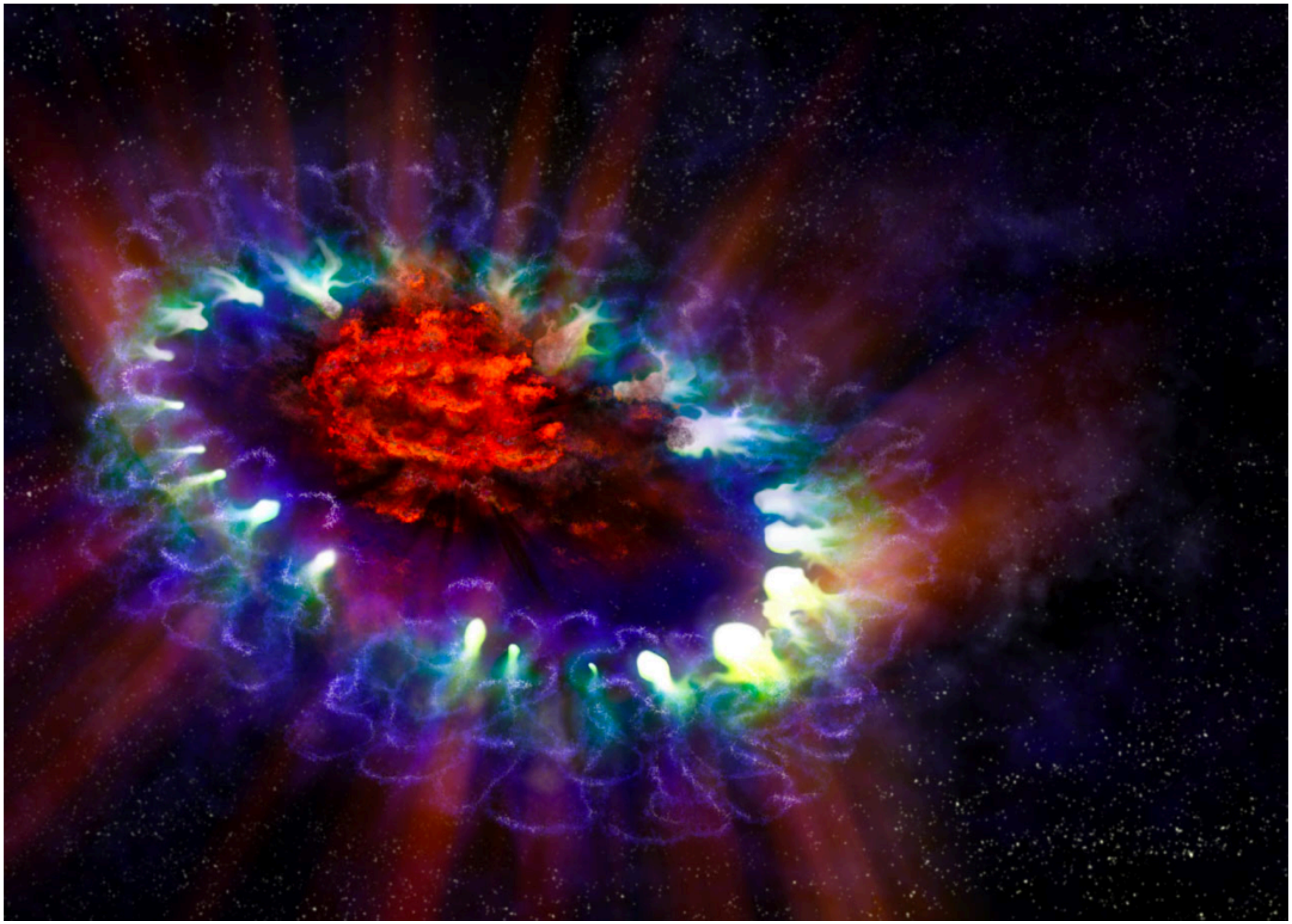
A loose thread





What are they?
Where do they come from?
How do they get such high energies?

Fermi acceleration



Doesn't explain the very highest energies

GZK cutoff

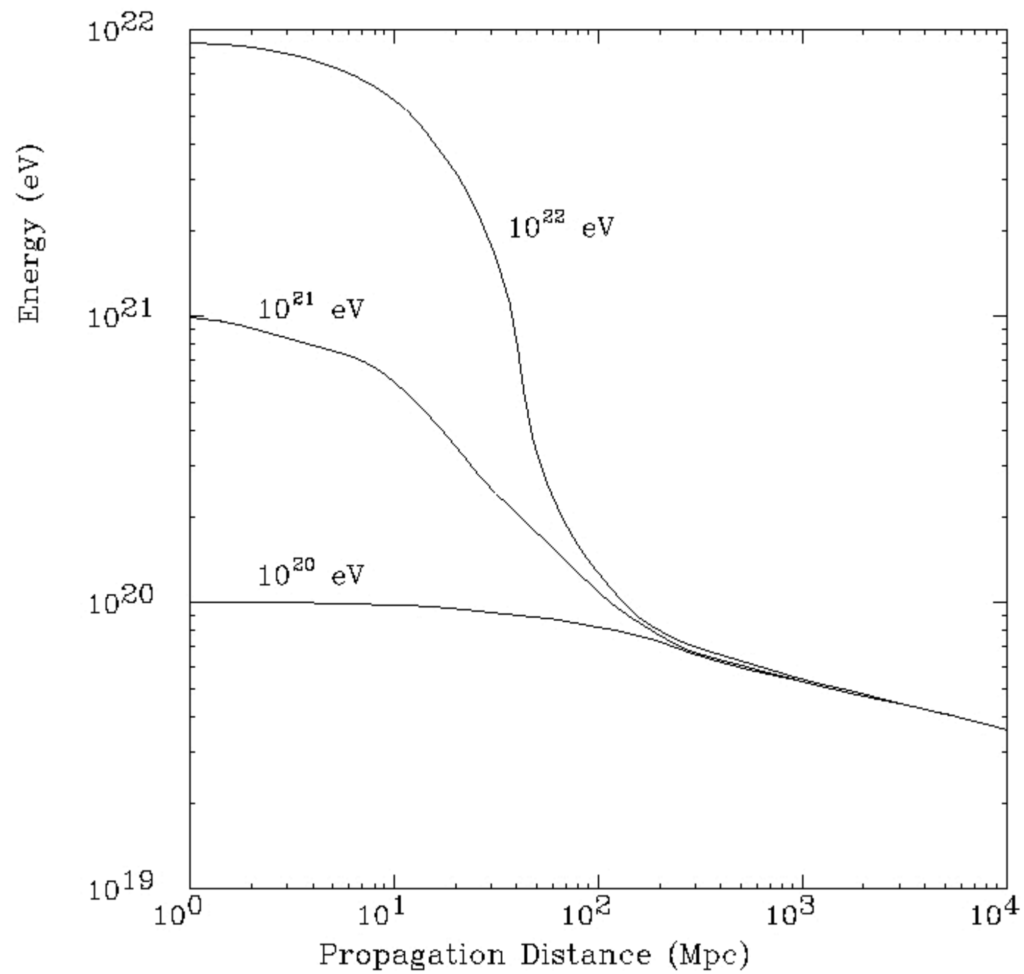
$$\gamma_{\rm CMB} + p \rightarrow \Delta^+ \rightarrow p + \pi^0,$$

Energy

At very high energies interaction with CMB degrades energy

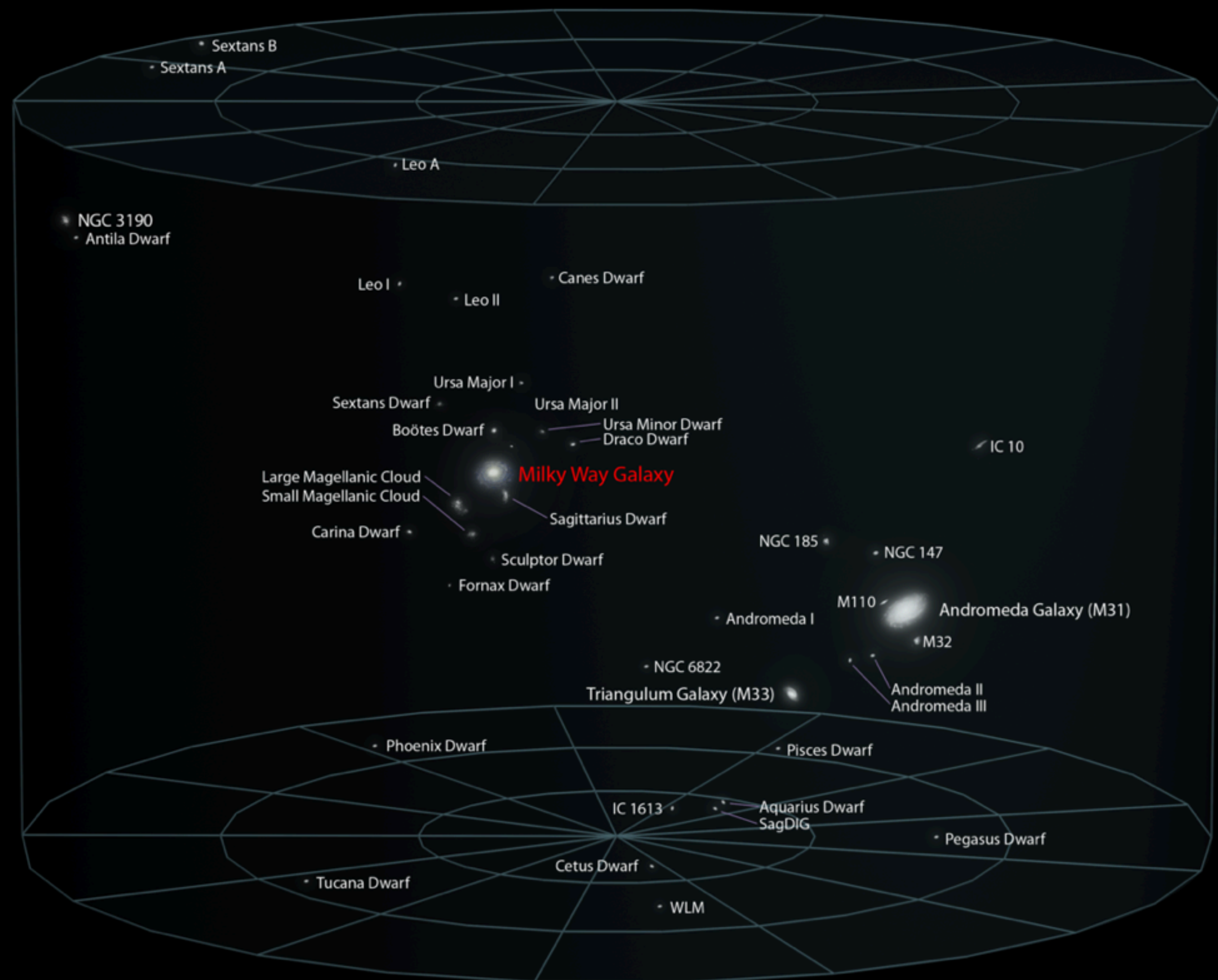
Distance

UHECRs cannot travel very far!



Our galaxy ~30kpc, Virgo cluster is 16.5 Mpc

Local Galactic Group



Our galaxy 30kpc, Local group 3Mpc, Virgo cluster 16.5 Mpc

Source of UHECR

Some unknown nearby object
is capable of generating
particles with energy >= 10^{20} eV

1503.01509

SETI AT PLANCK ENERGY: WHEN PARTICLE PHYSICISTS BECOME COSMIC ENGINEERS

BRIAN C. LACKI
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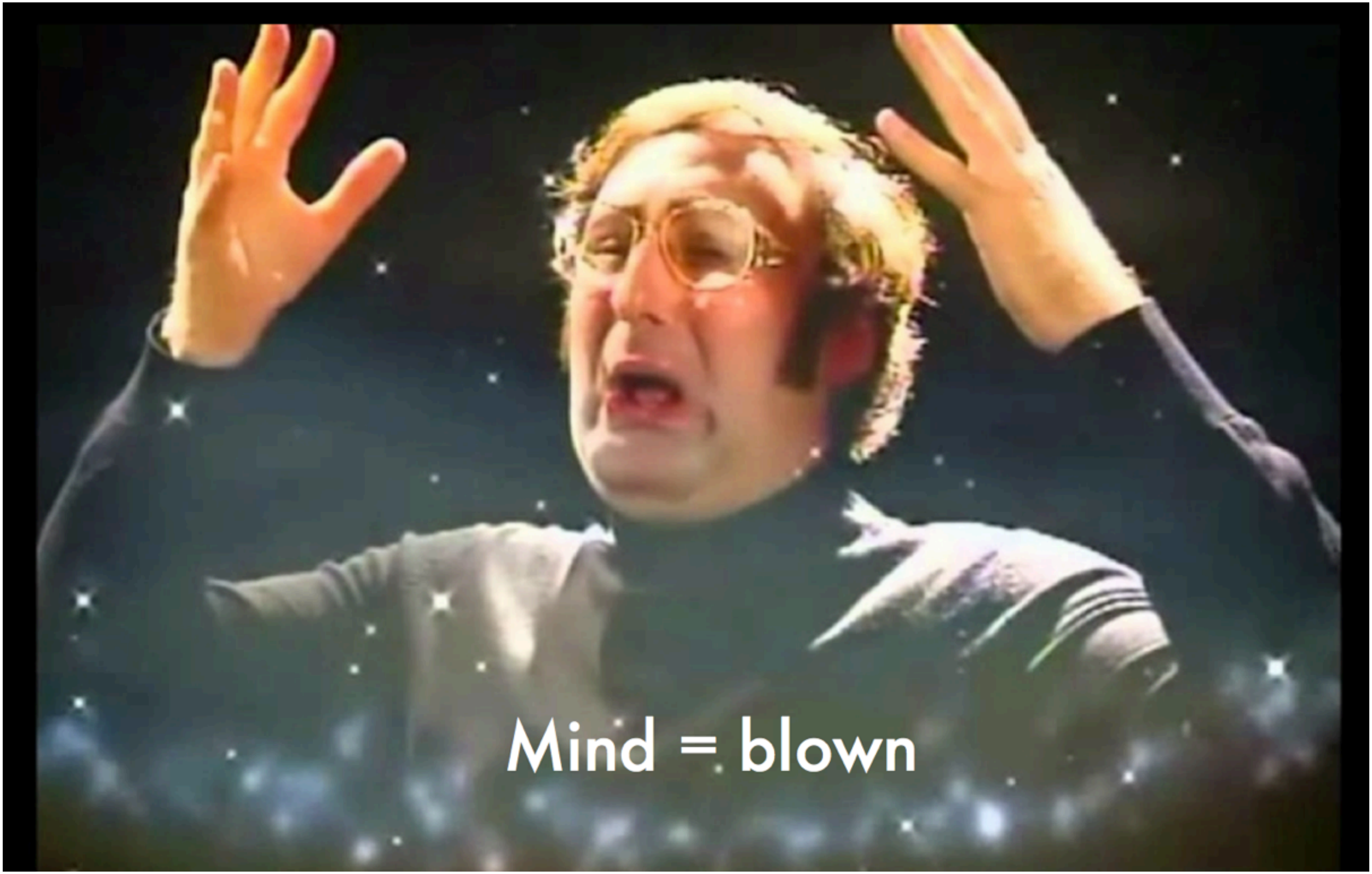
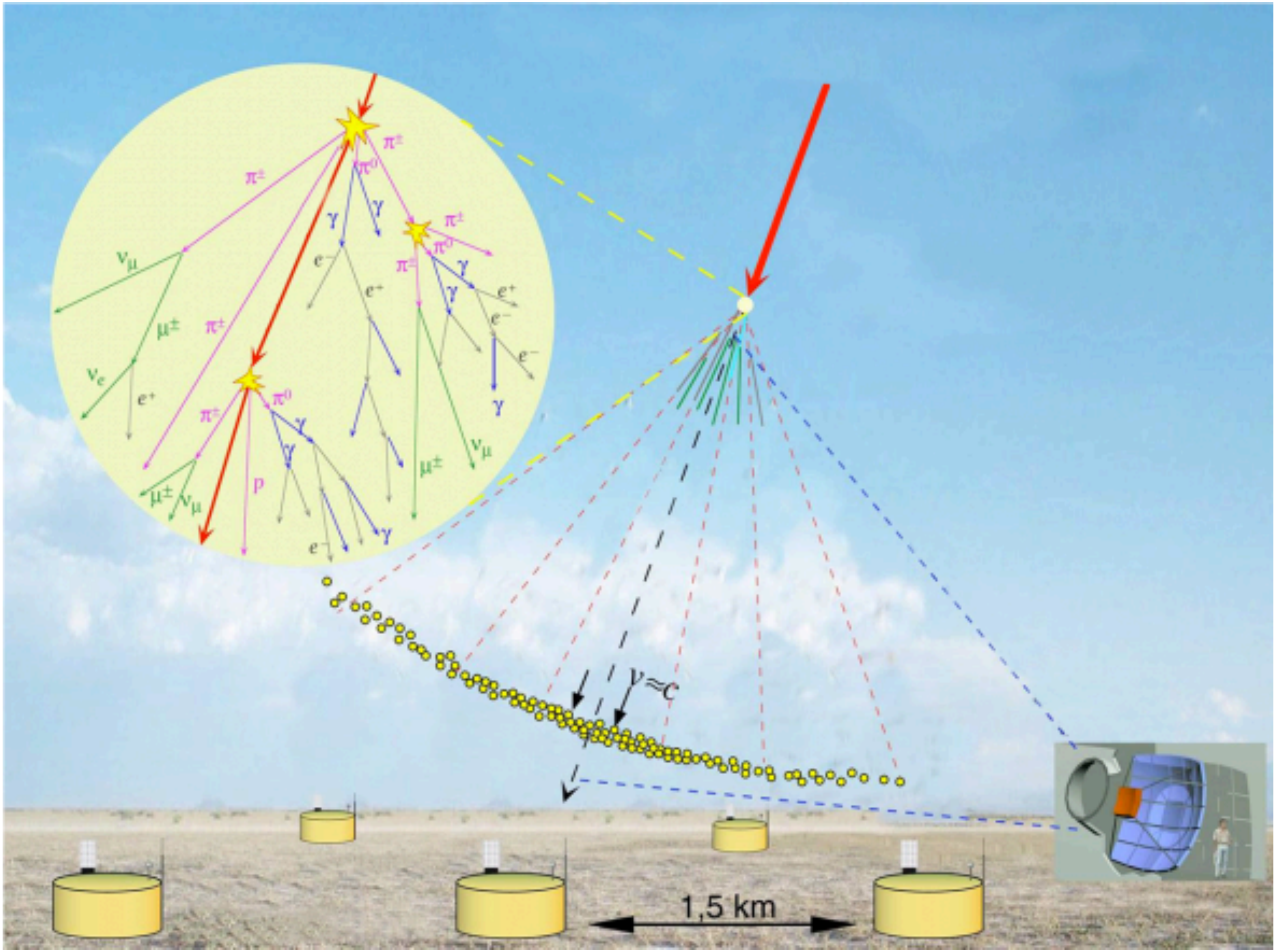
Draft version March 6, 2015

ABSTRACT

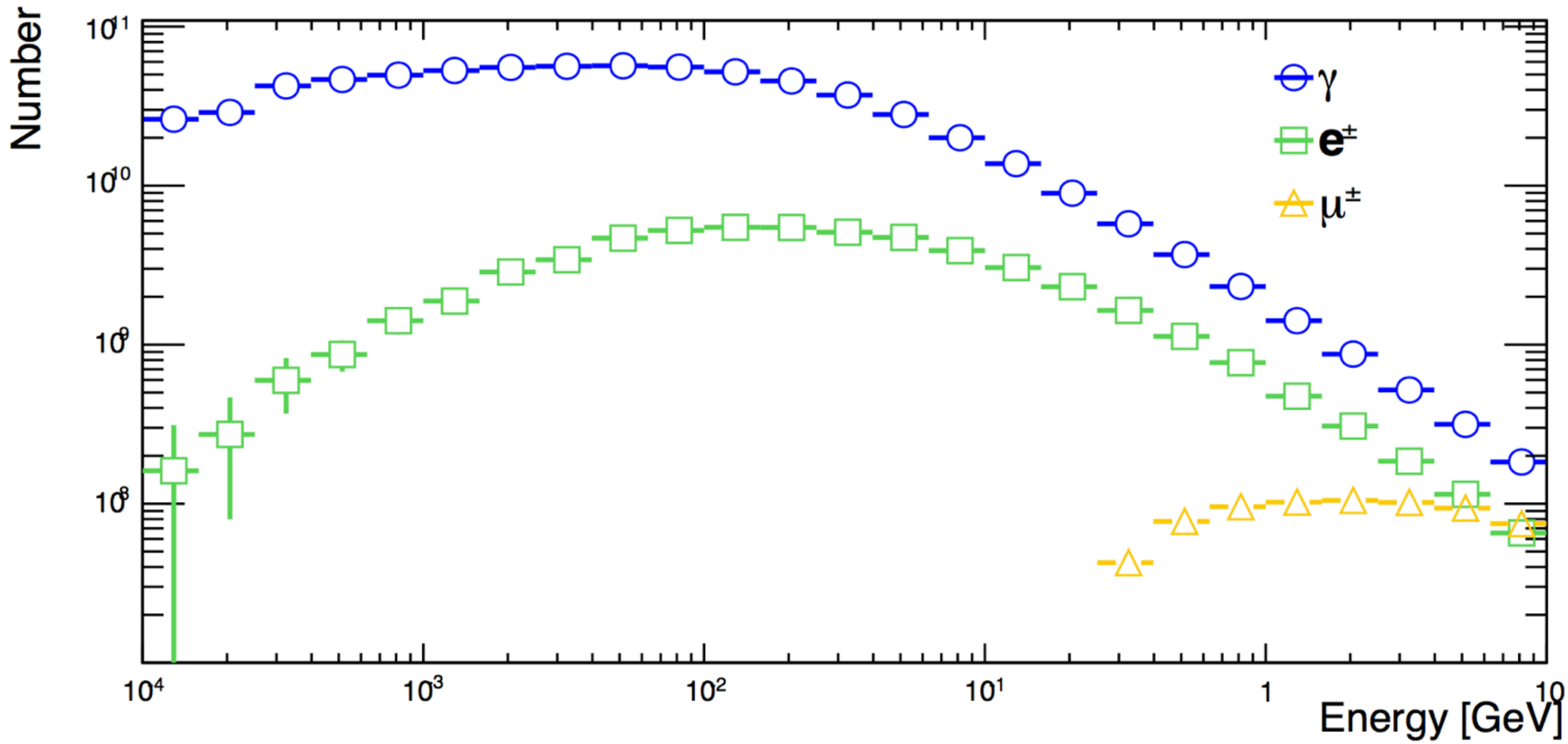
What is the meaning of the Fermi Paradox – are we alone or is starfaring rare? Can general relativity be united with quantum mechanics? The searches for answers to these questions could intersect. It is known that an accelerator capable of energizing particles to the Planck scale requires cosmic proportions. The energy required to run a Planck accelerator is also cosmic, of order 100 $M_{\odot}c^2$ for a hadron collider, because the natural cross section for Planck physics is so tiny. If aliens are interested in fundamental physics, they could resort to cosmic engineering for their experiments. These colliders are detectable through the vast amount of "pollution" they produce, motivating a YeV SETI program. I investigate what kinds of radiation they would emit in a fireball scenario, and the feasibility of detecting YeV radiation at Earth, particularly YeV neutrinos. Although current limits on YeV neutrinos are weak, Kardashev 3 YeV neutrino sources appear to be at least 30–100 Mpc apart on average, if they are long-lived and emit isotropically. I consider the feasibility of much larger YeV neutrino detectors, including an acoustic detection experiment that spans all of Earth's oceans, and instrumenting the entire Kuiper Belt. Any detection of YeV neutrinos implies an extraordinary phenomenon at work, whether artificial and natural. Searches for YeV neutrinos from any source are naturally commensal, so a YeV neutrino SETI program has value beyond SETI itself, particularly in limiting topological defects. I note that the Universe is very faint in all kinds of nonthermal radiation, indicating that cosmic engineering is extremely rare.


Mind = blown

Observing UHECR

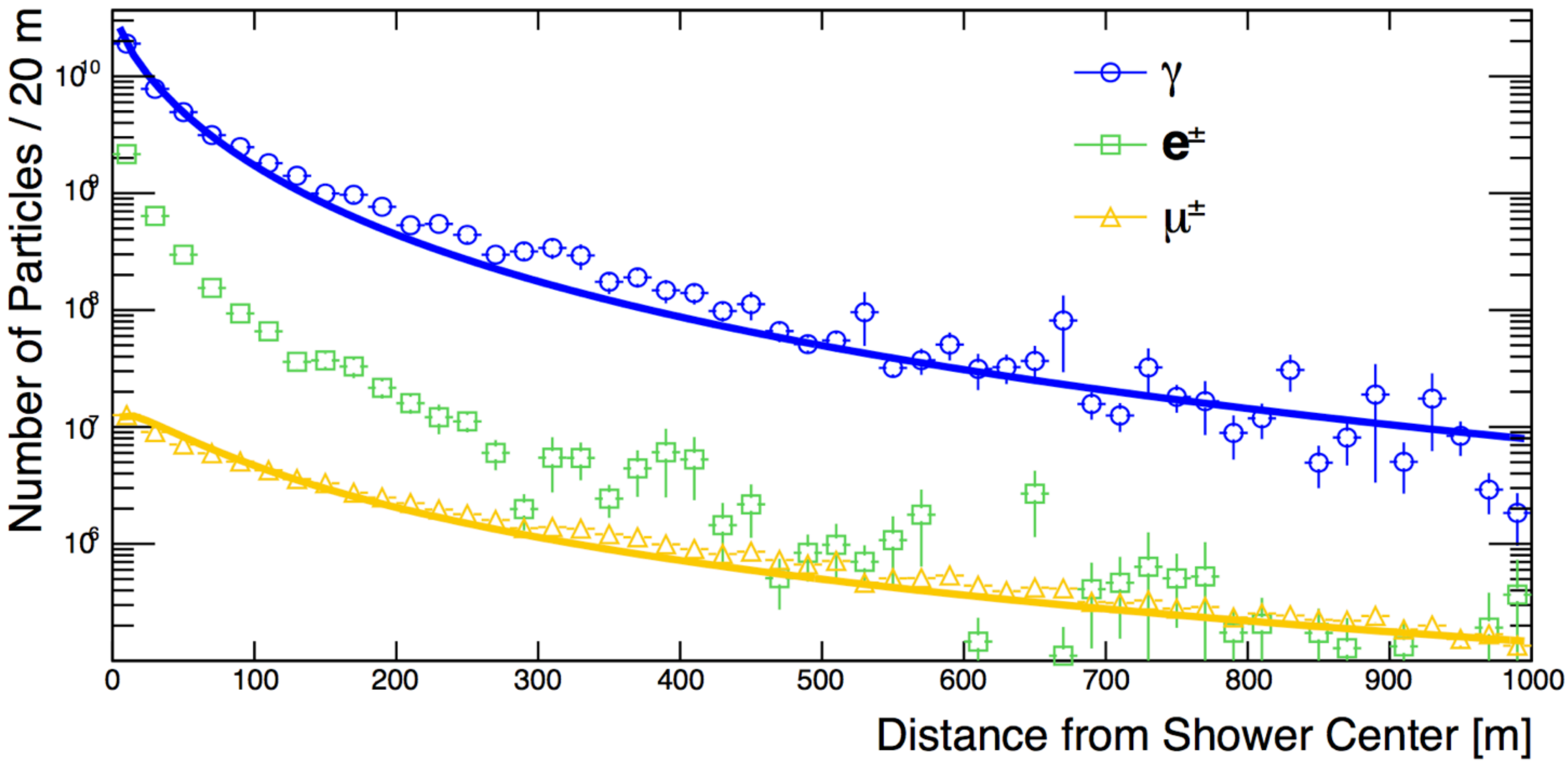

1,5 km

What’s in an airshower?



CORSIKA simulation, E = 10^{19} eV

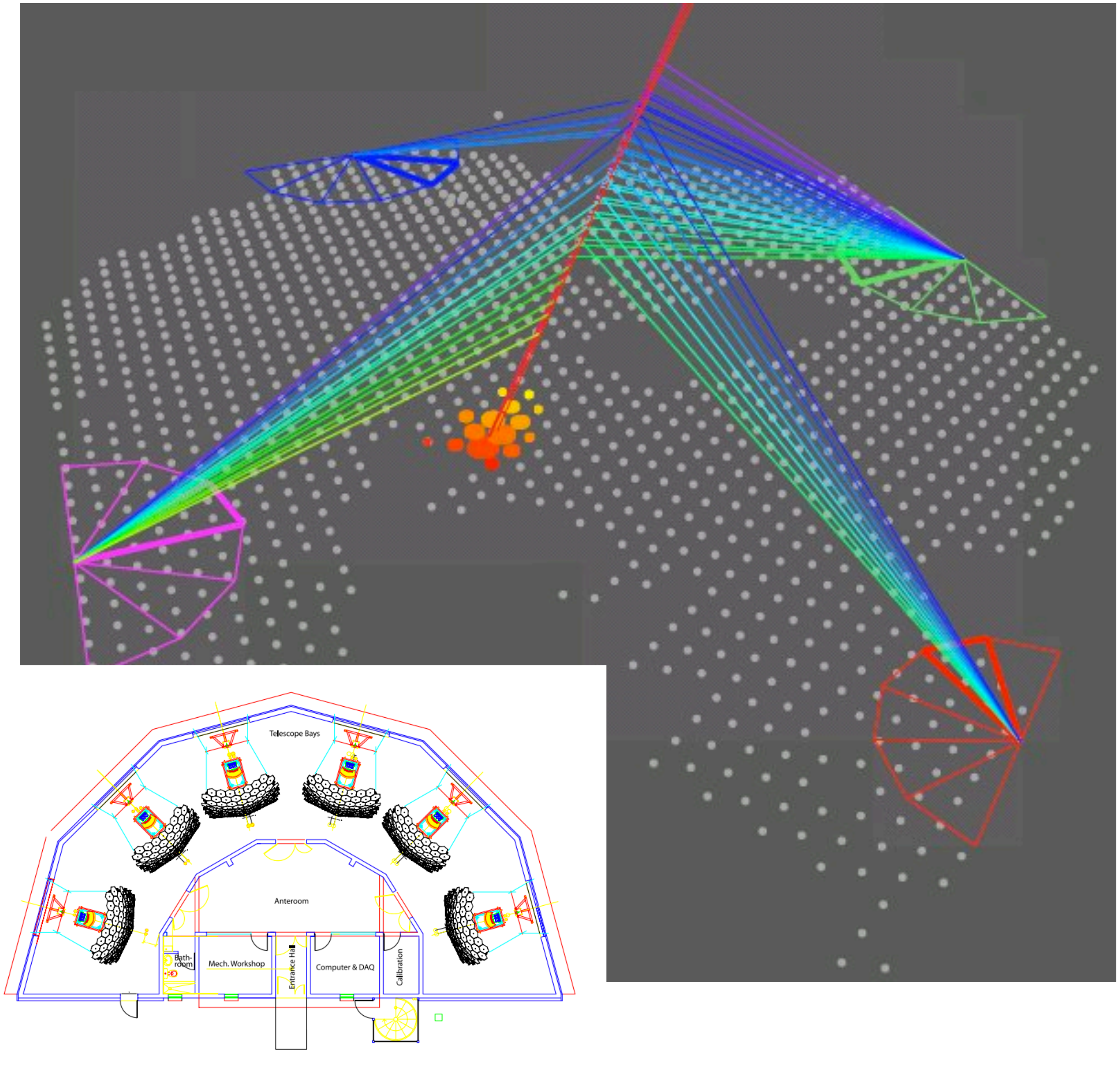
Distribution



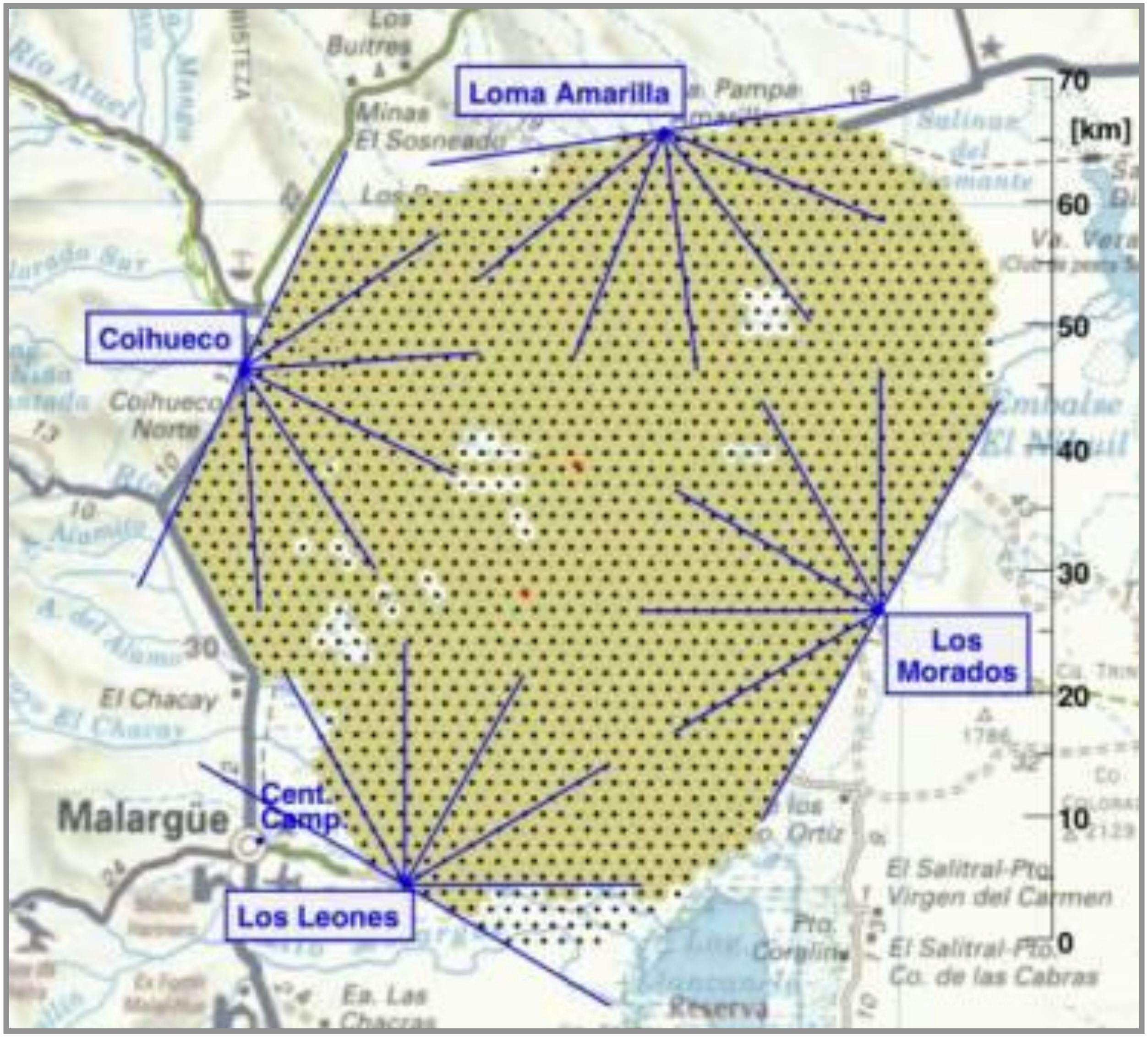
CORSIKA simulation, $E = 10^{19}$ eV

Flourescence

Excited
atmospheric
nitrogen

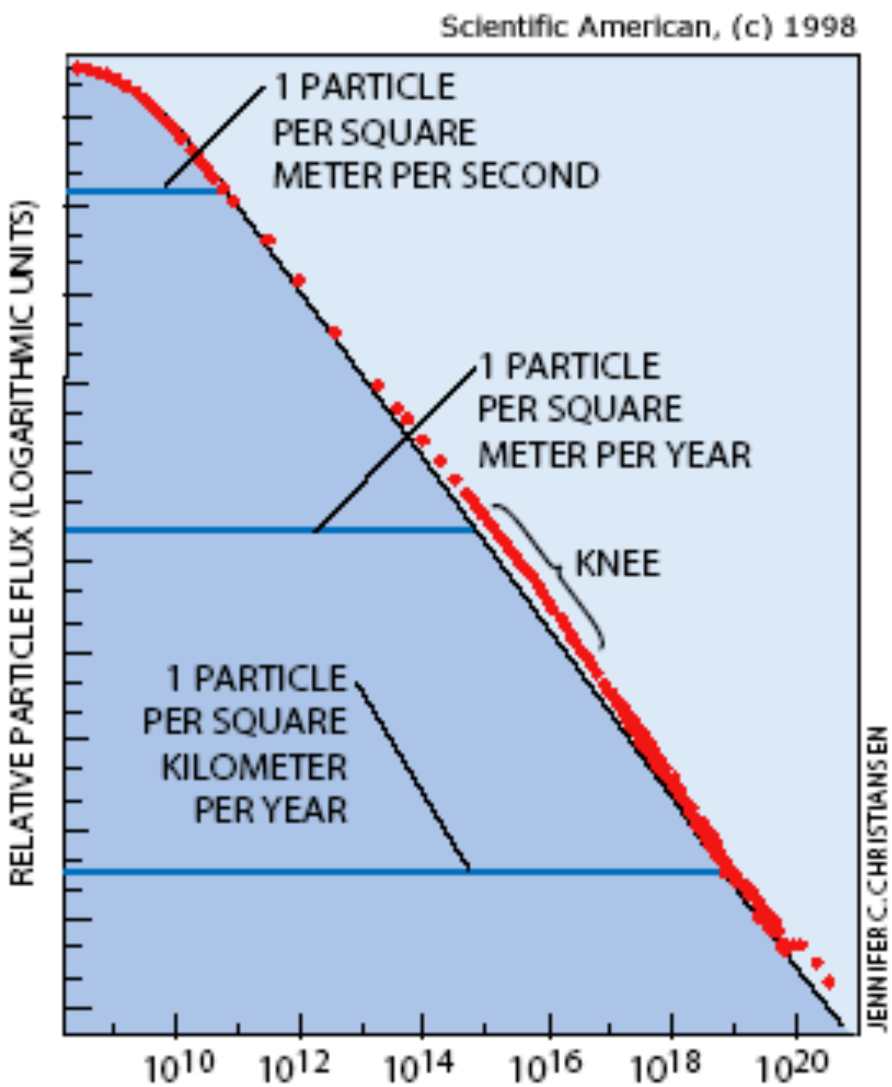


Auger



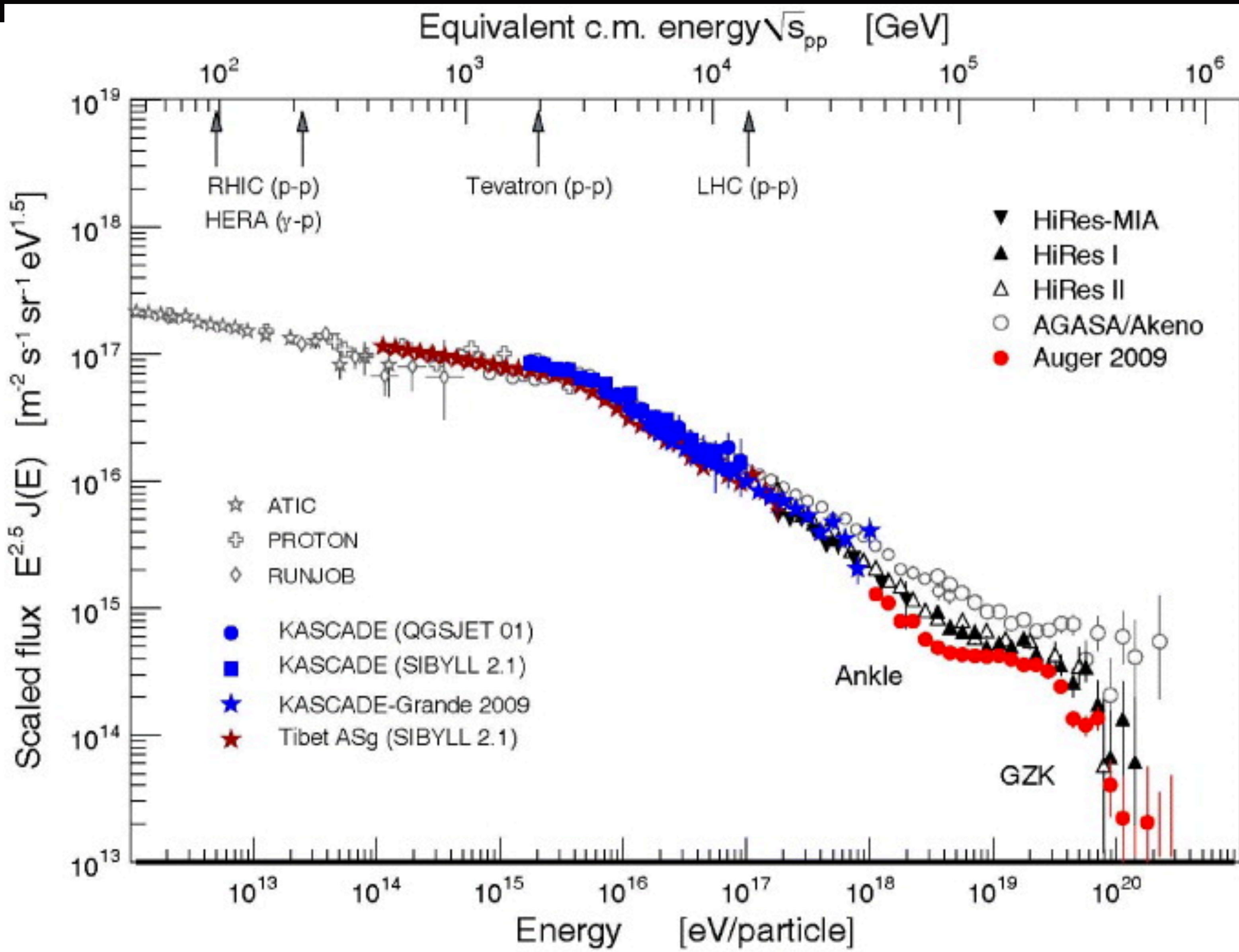
PIERRE AUGER OBSERVATORY

But rare!!



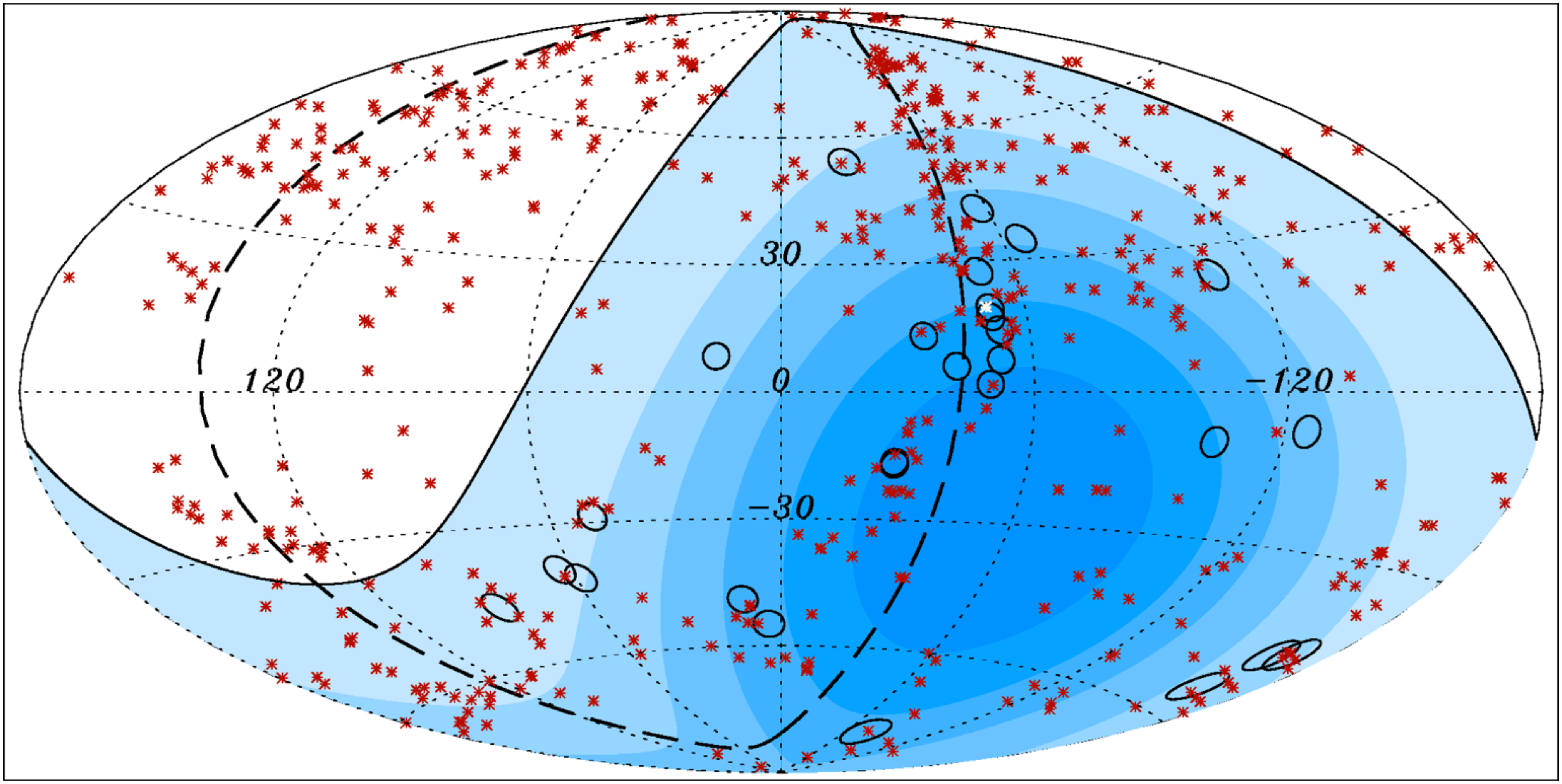
Scientific American, (c) 1998
1 PARTICLE PER SQUARE METER PER SECOND
1 PARTICLE PER SQUARE METER PER YEAR
KNEE
1 PARTICLE PER SQUARE KILOMETER PER YEAR
RELATIVE PARTICLE FLUX (LOGARITHMIC UNITS)
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
JENNIFER C. CHRISTIANSEN

Spectrum

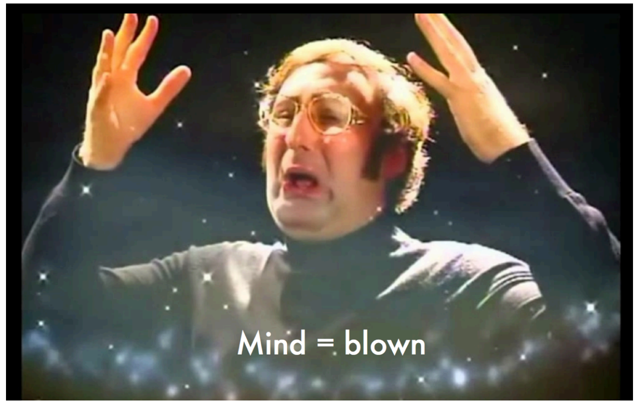


Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
AGASA/Akeno
Auger 2009
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Ankle
GZK
Scaled flux $E^{2.5} J(E)$ [$m^{-2} s^{-1} sr^{-1} eV^{1.5}$]
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy [eV/particle]

Auger results



Circles are CR with $E > 5 \times 10^{19}$ eV; red are AGN



NT@UW-12-14
INT-PUB-12-046

Constraints on the Universe as a Numerical Simulation

Silas R. Beane,[1,2,*] Zohreh Davoudi,[3,†] and Martin J. Savage[3,‡]

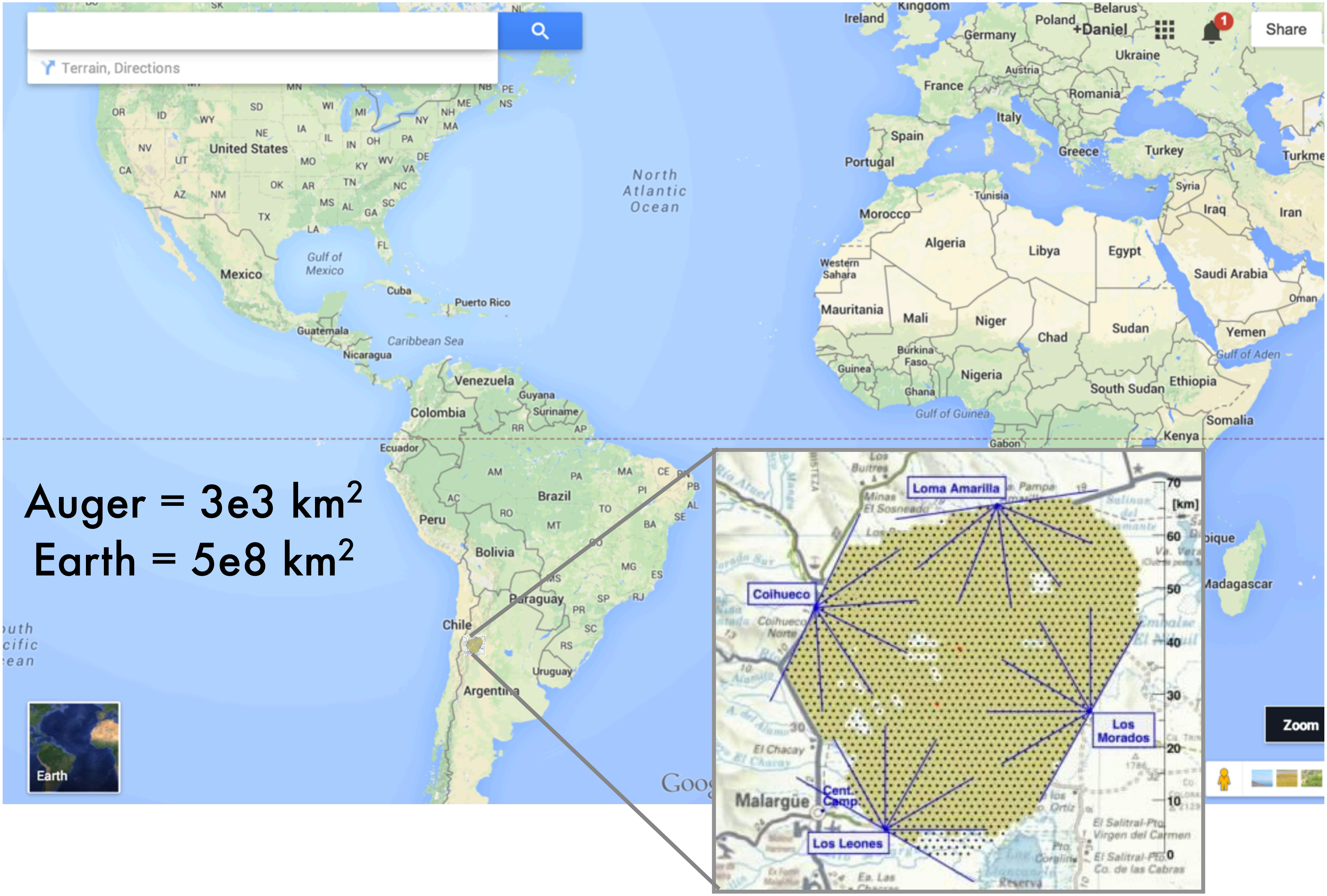
[1]*Institute for Nuclear Theory, Box 351550, Seattle, WA 98195-1550, USA*
[2]*Helmholtz-Institut für Strahlen- und Kernphysik (Theorie), Universität Bonn, D-53115 Bonn, Germany*
[3]*Department of Physics, University of Washington, Box 351560, Seattle, WA 98195, USA*

(Dated: November 12, 2012 - 1:14)

Abstract

Observable consequences of the hypothesis that the observed universe is a numerical simulation performed on a cubic space-time lattice or grid are explored. The simulation scenario is first motivated by extrapolating current trends in computational resource requirements for lattice QCD into the future. Using the historical development of lattice gauge theory technology as a guide, we assume that our universe is an early numerical simulation with unimproved Wilson fermion discretization and investigate potentially-observable consequences. Among the observables that are considered are the muon $g-2$ and the current differences between determinations of α, but the most stringent bound on the inverse lattice spacing of the universe, $b^{-1} \gtrsim 10^{11}$ GeV, is derived from the high-energy cut off of the cosmic ray spectrum. The numerical simulation scenario could reveal itself in the distributions of the highest energy cosmic rays exhibiting a degree of rotational symmetry breaking that reflects the structure of the underlying lattice.

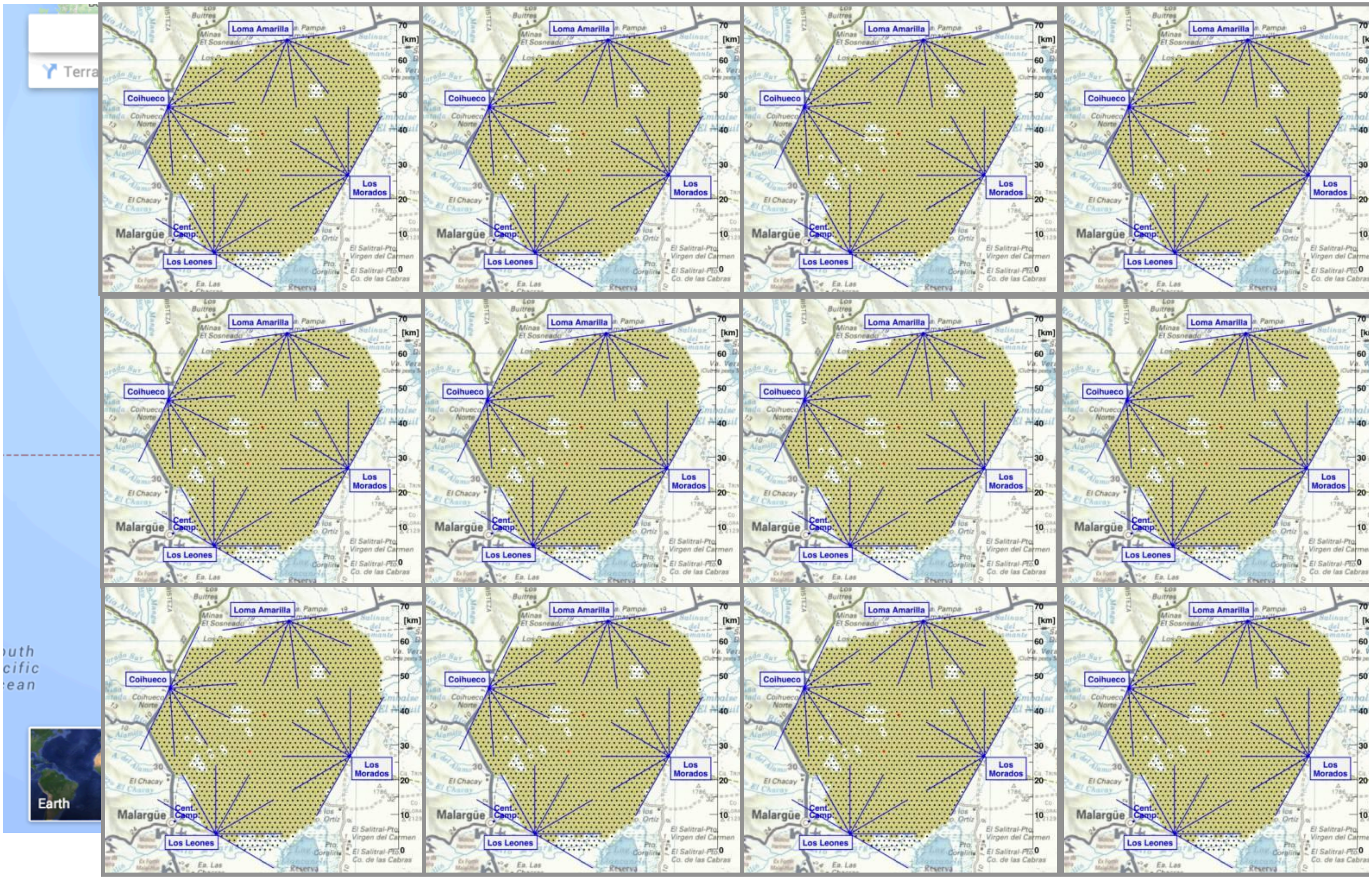
Auger captures a tiny fraction of cosmic rays



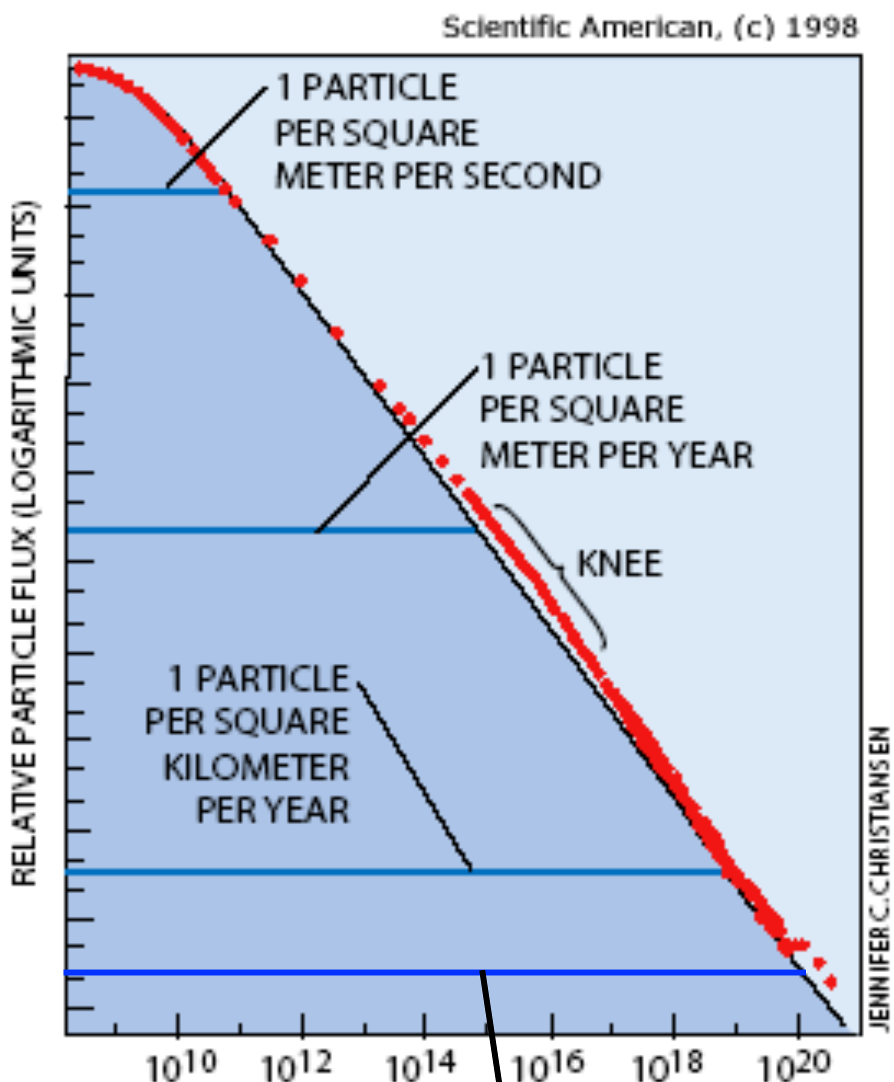
Auger = 3e3 km^2

Earth = 5e8 km^2

How to get more events?



Earth scales



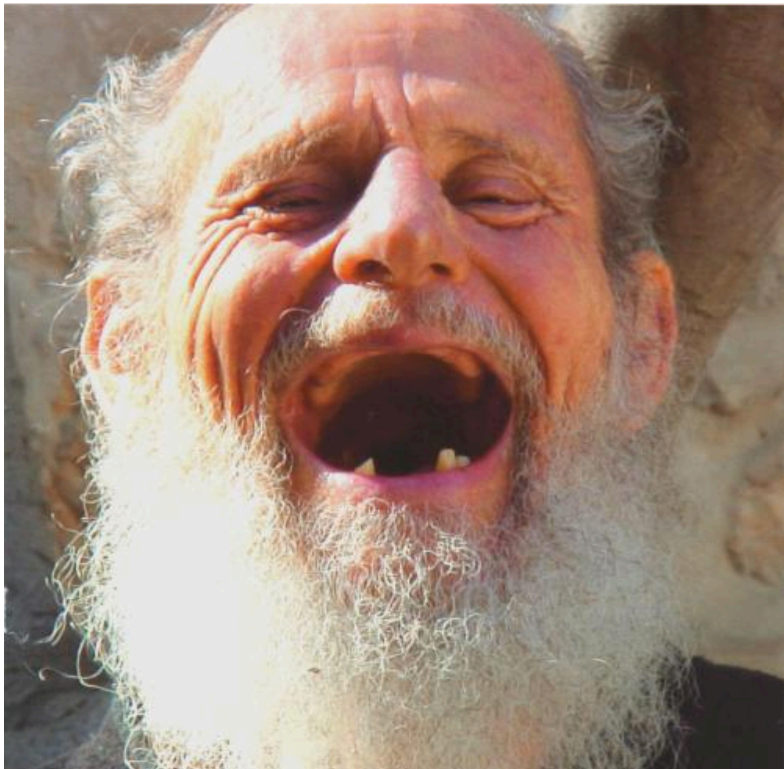
5e12 particles/year

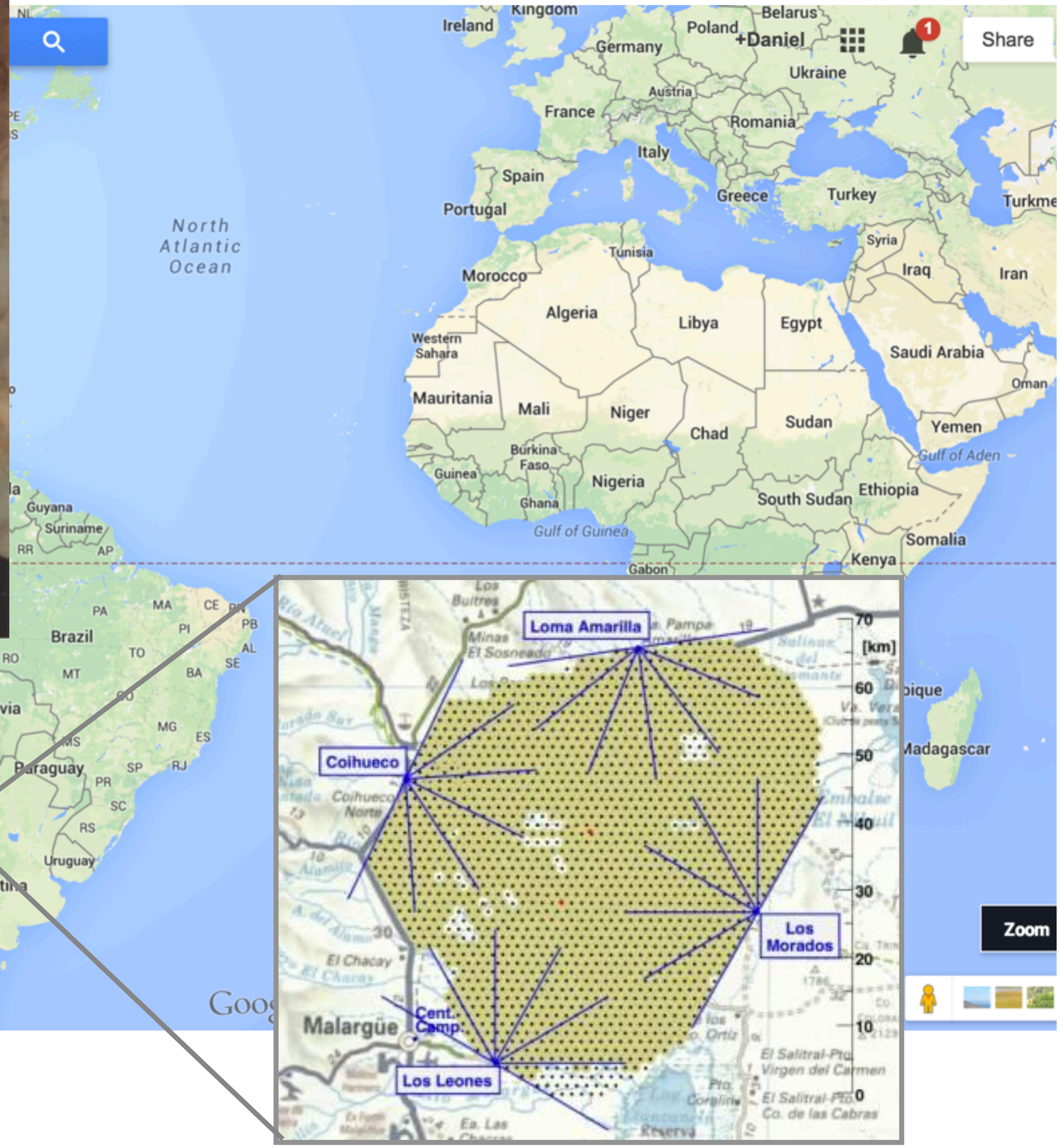
5e8 particles/year

5e6 particles/year

1 particle per
square km
per century

How to get more events?



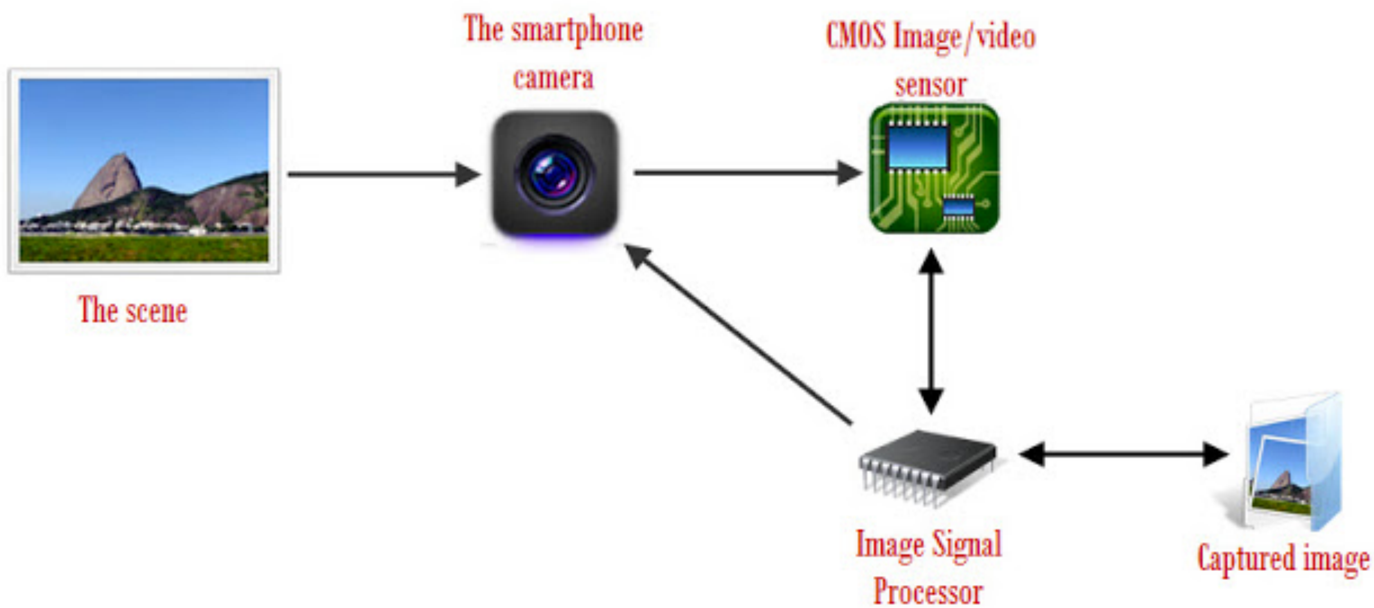


Need

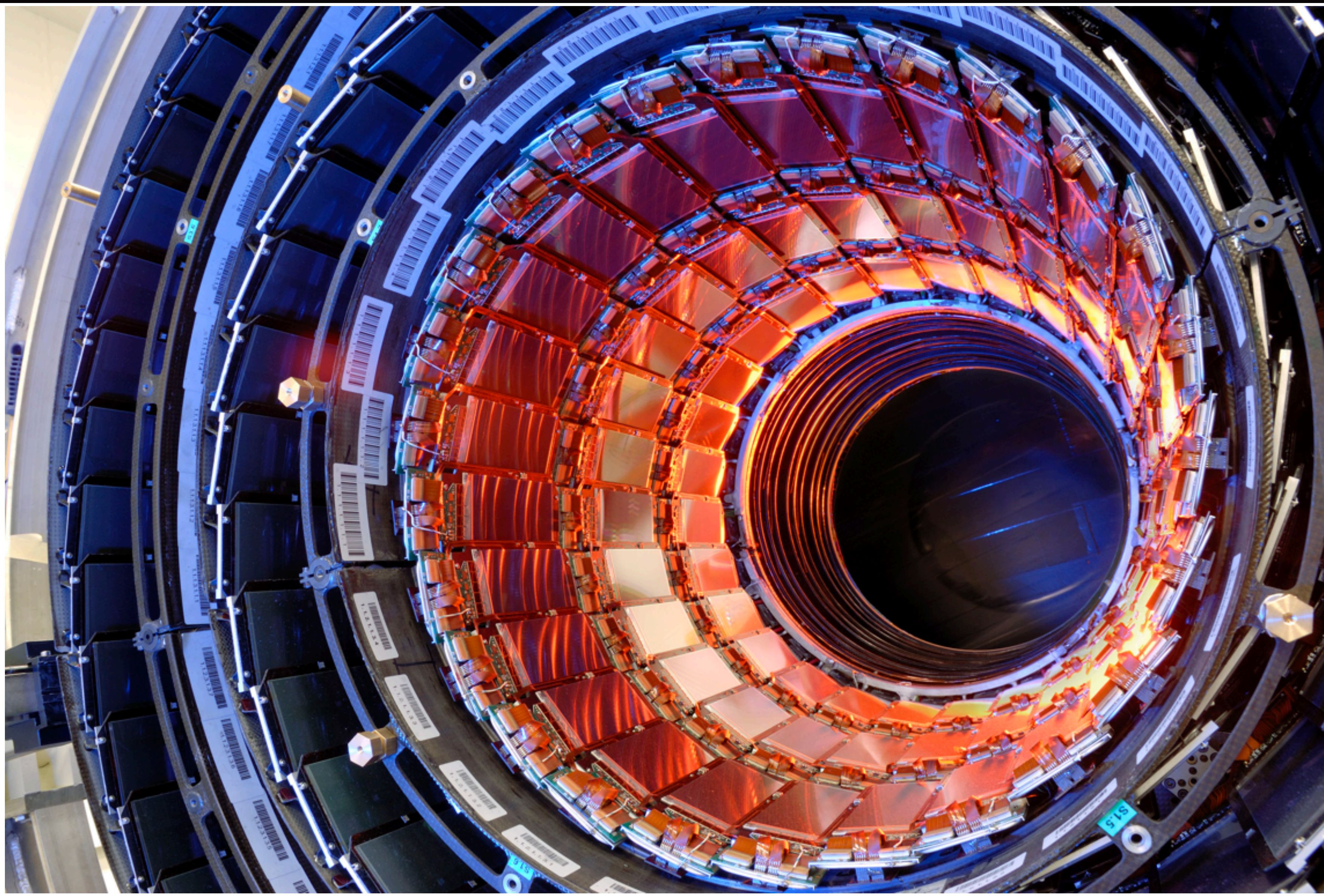
<u>Wishlist</u>

Planet-sized ground array
Existing or free devices
Wireless data upload
Remotely programmable
Maintained by dedicated shifters

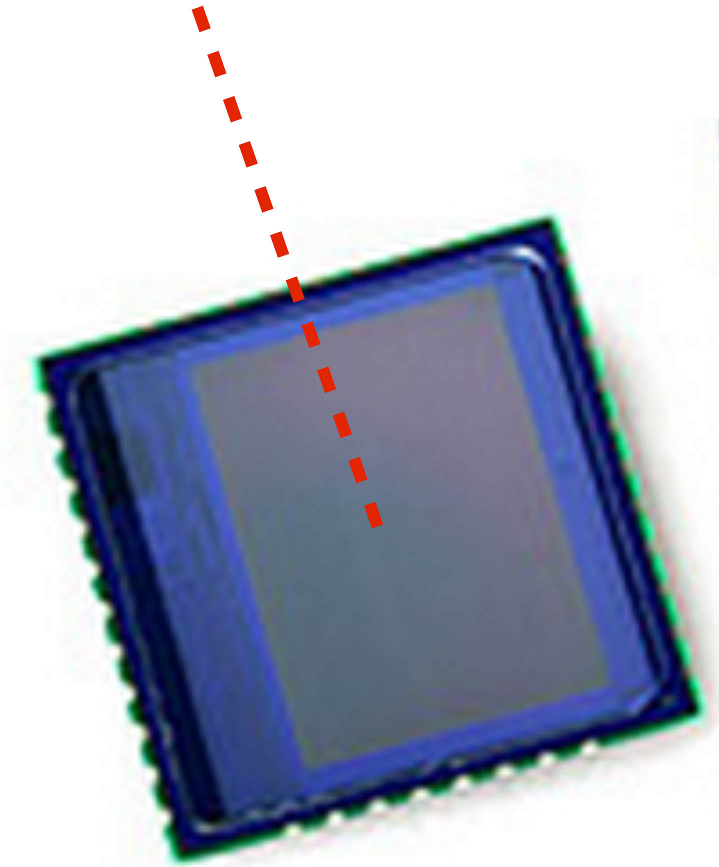
Smartphones



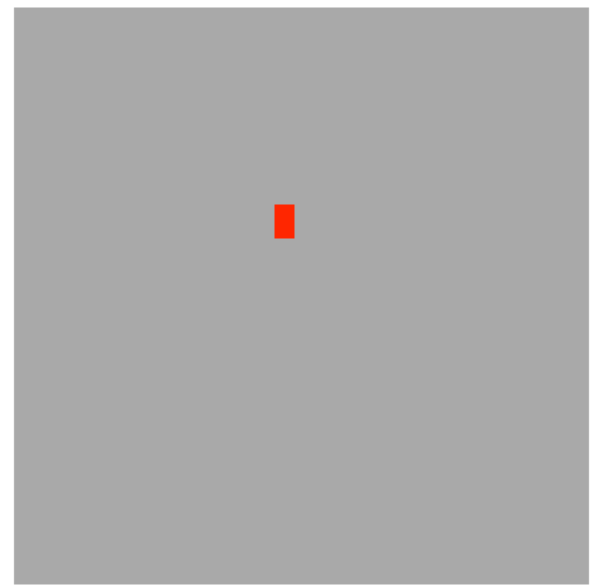
Familiar technology



Particle detector

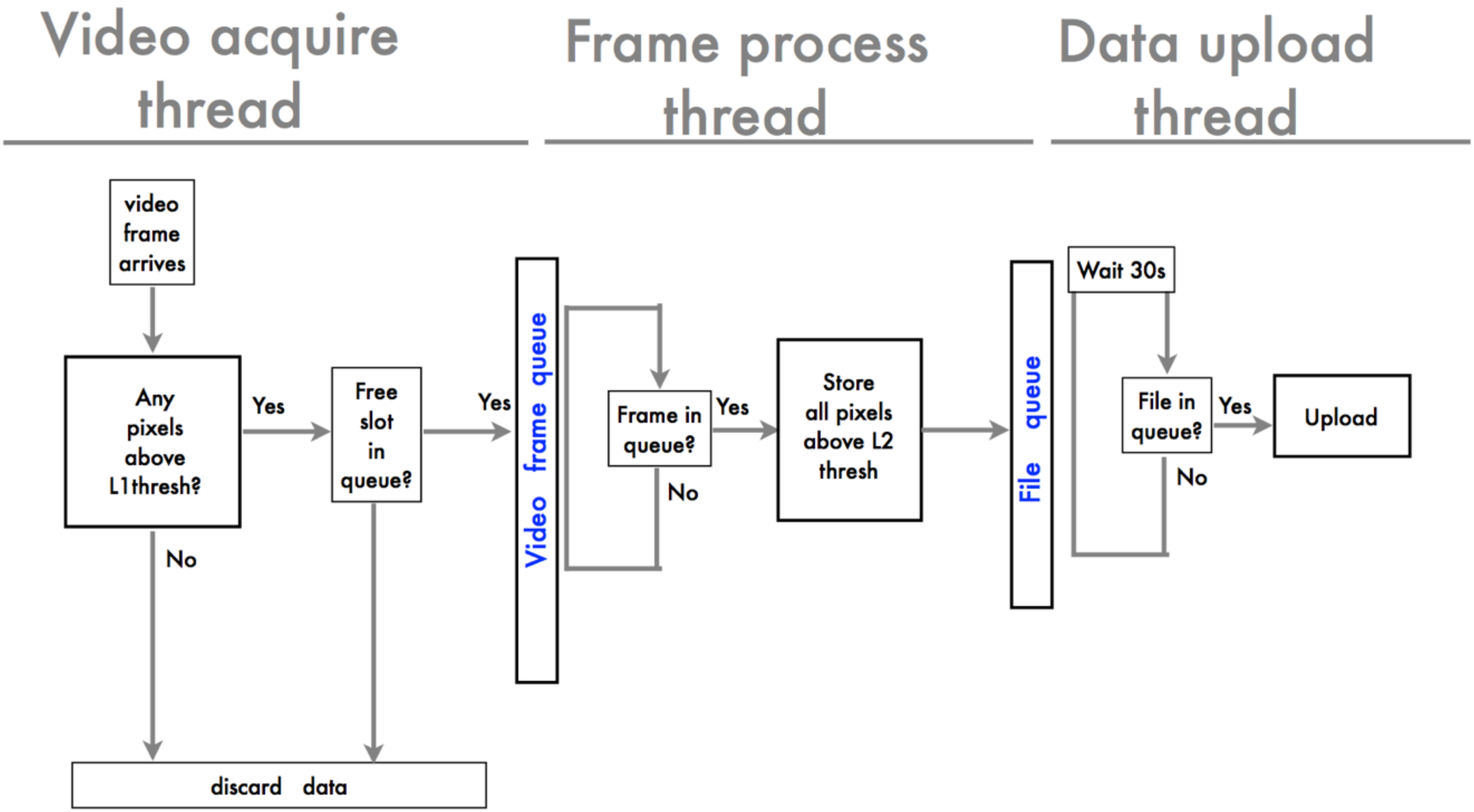


Particle incident
on CMOS chip



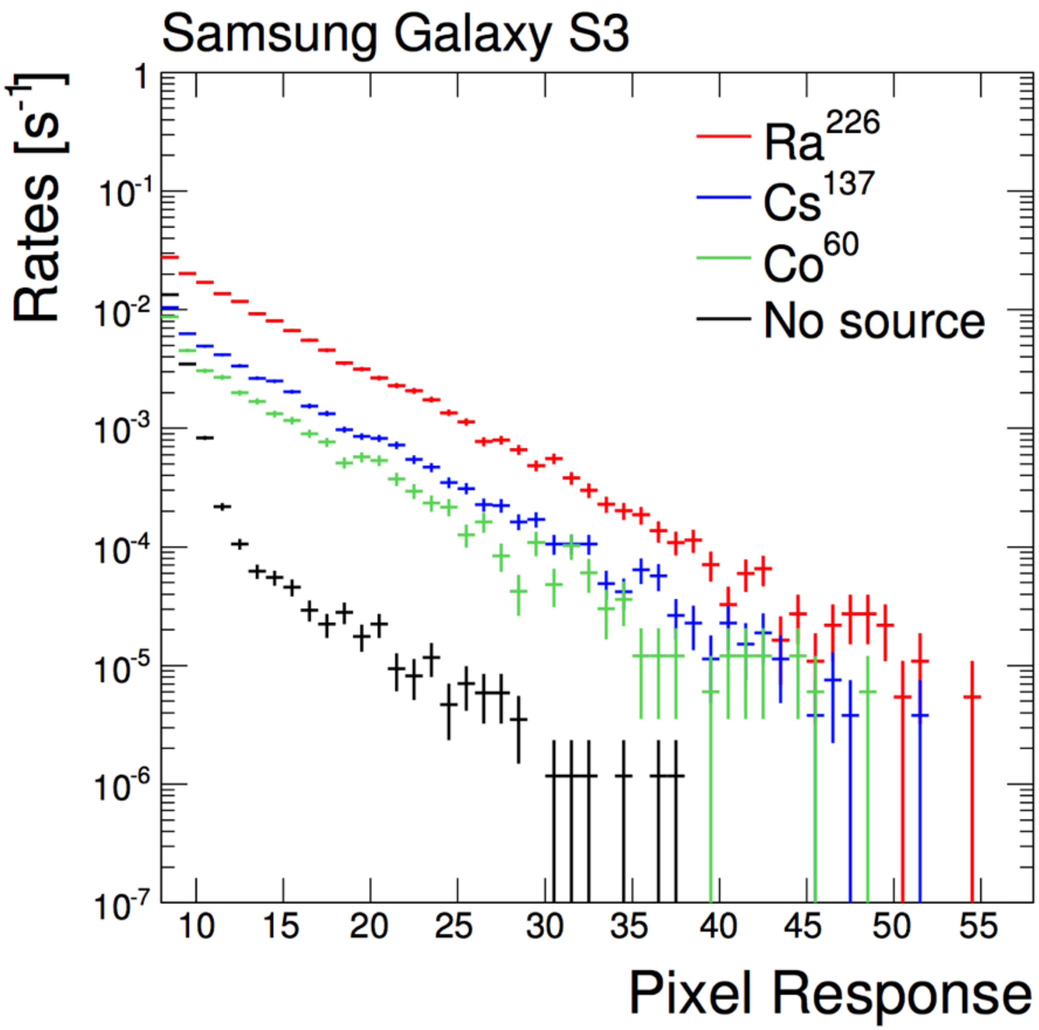
Hot pixel
in image

Software


Video acquire thread
Frame process thread
Data upload thread
video frame arrives
Any pixels above L1thresh?
Yes
No
Free slot in queue?
Yes
discard data
Video frame queue
Frame in queue?
Yes
No
Store all pixels above L2 thresh
File queue
Wait 30s
File in queue?
Yes
No
Upload

Photon sensitivity

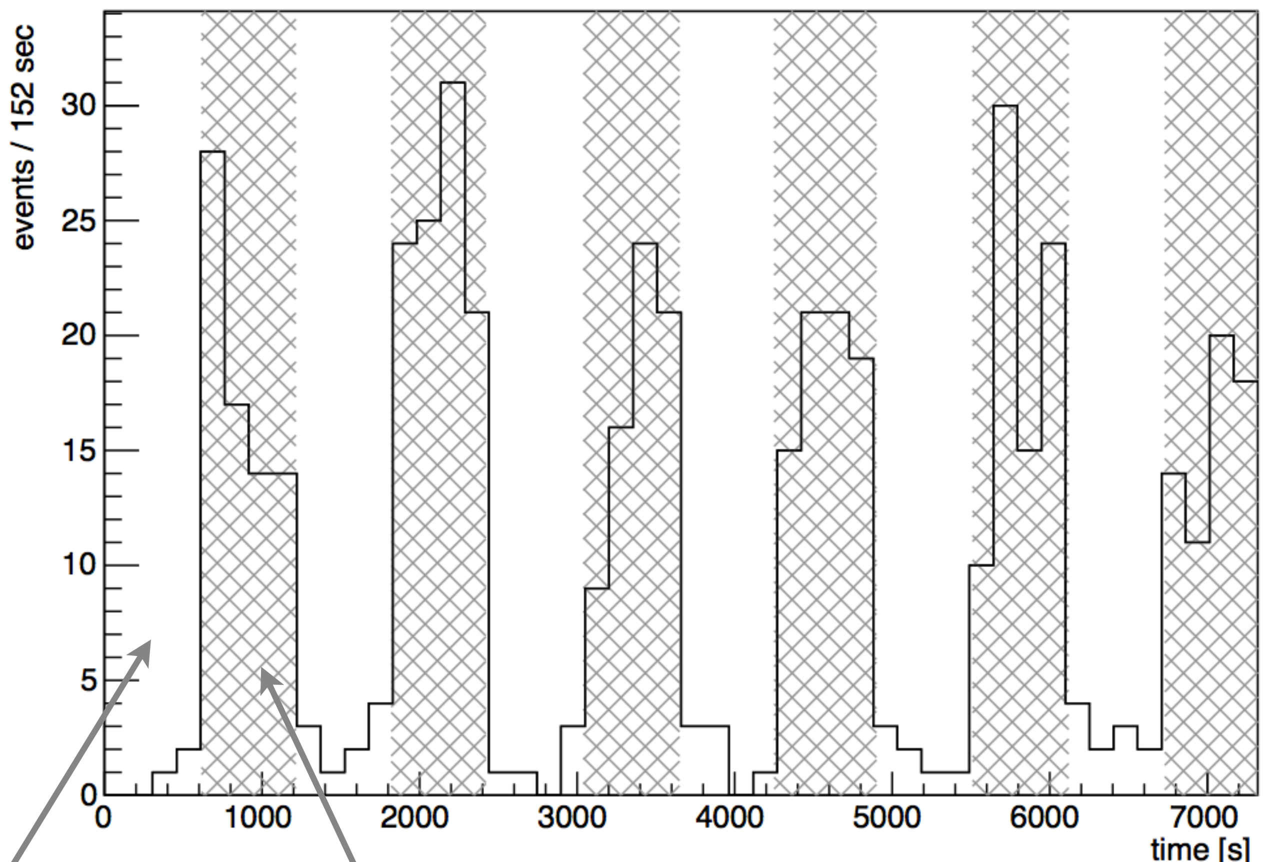
Sources



Sources held
at fixed distance
from phones.

Other devices give
qualitatively similar
spectra

Time-variation

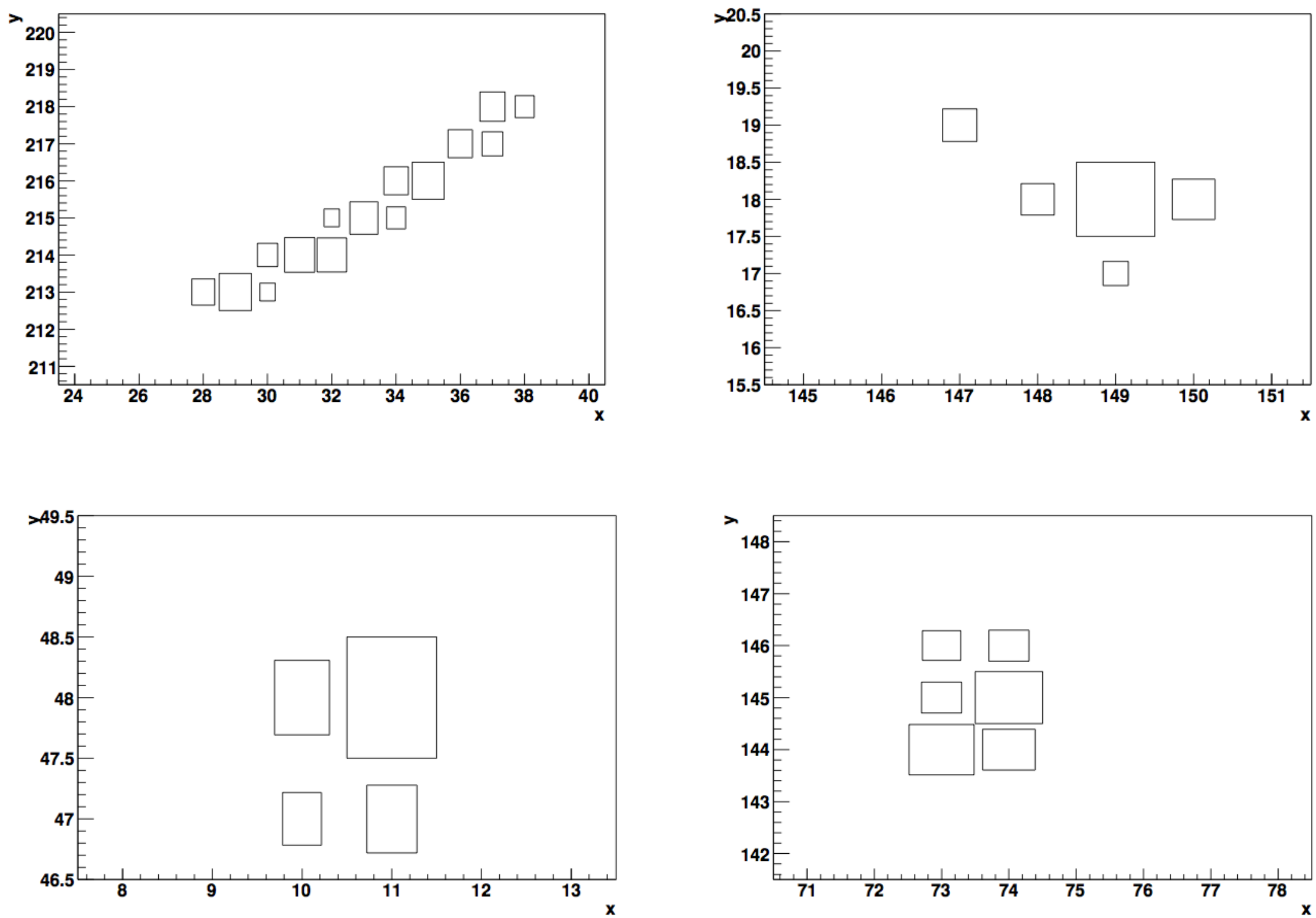


No source

Rad226

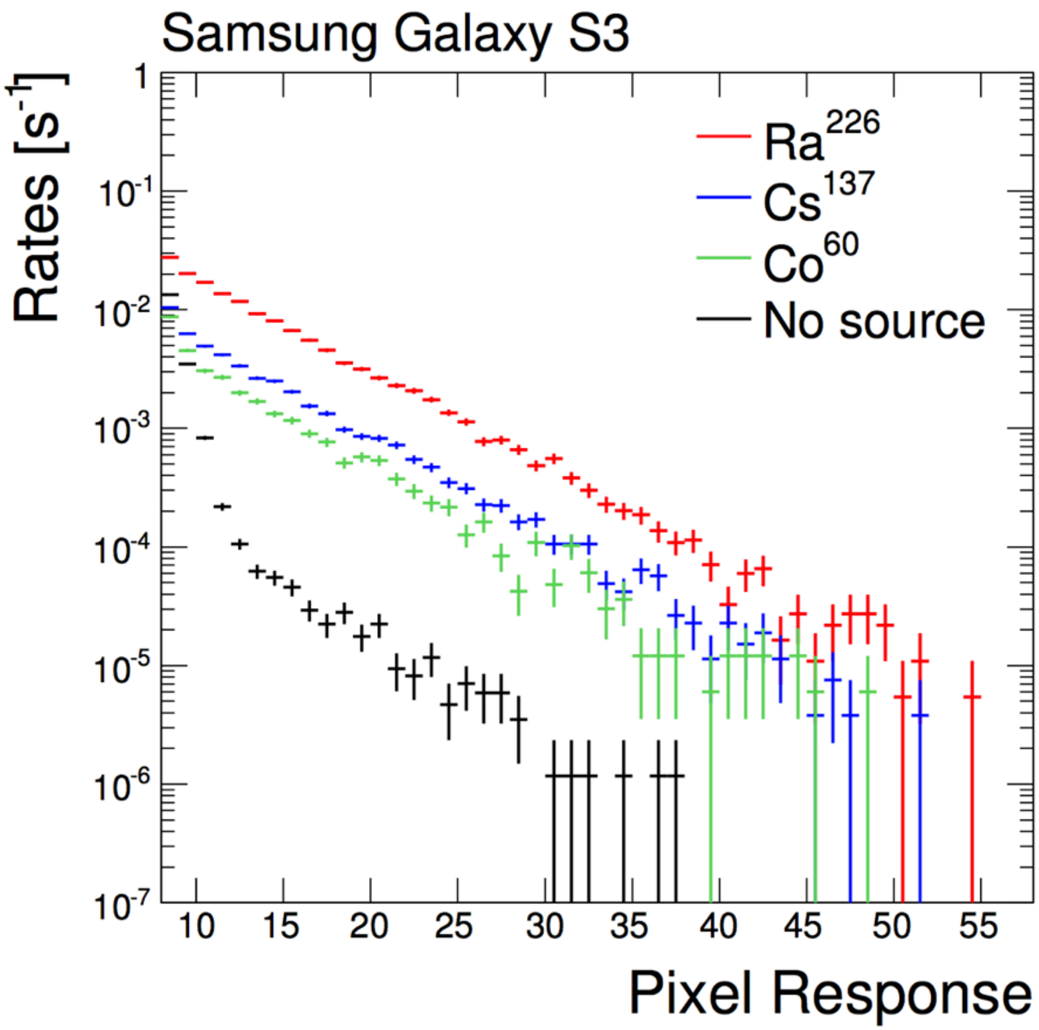
https://www.youtube.com/watch?v=ldDEFeKZ100

Individual hits



Muon sensitivity

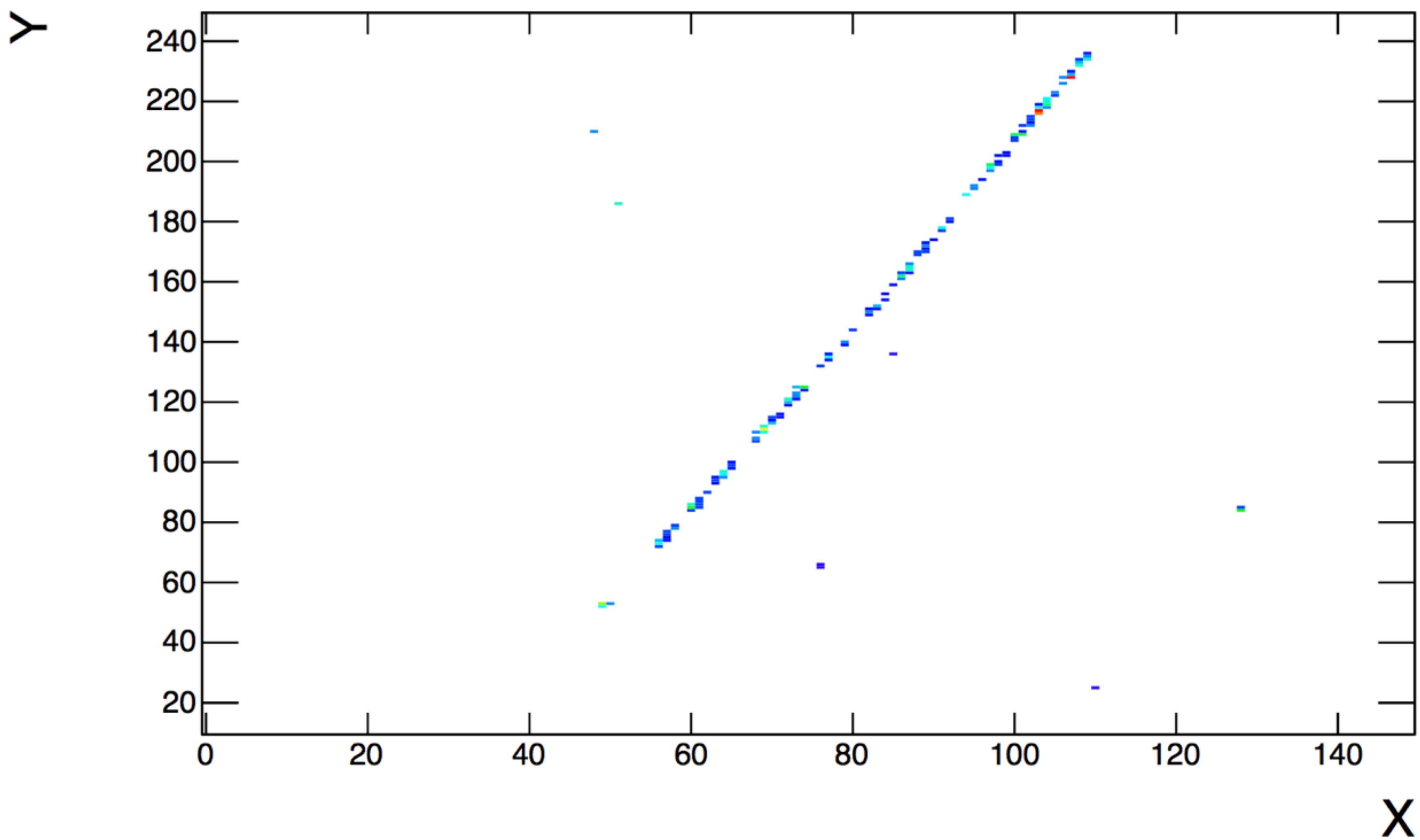
No source tails



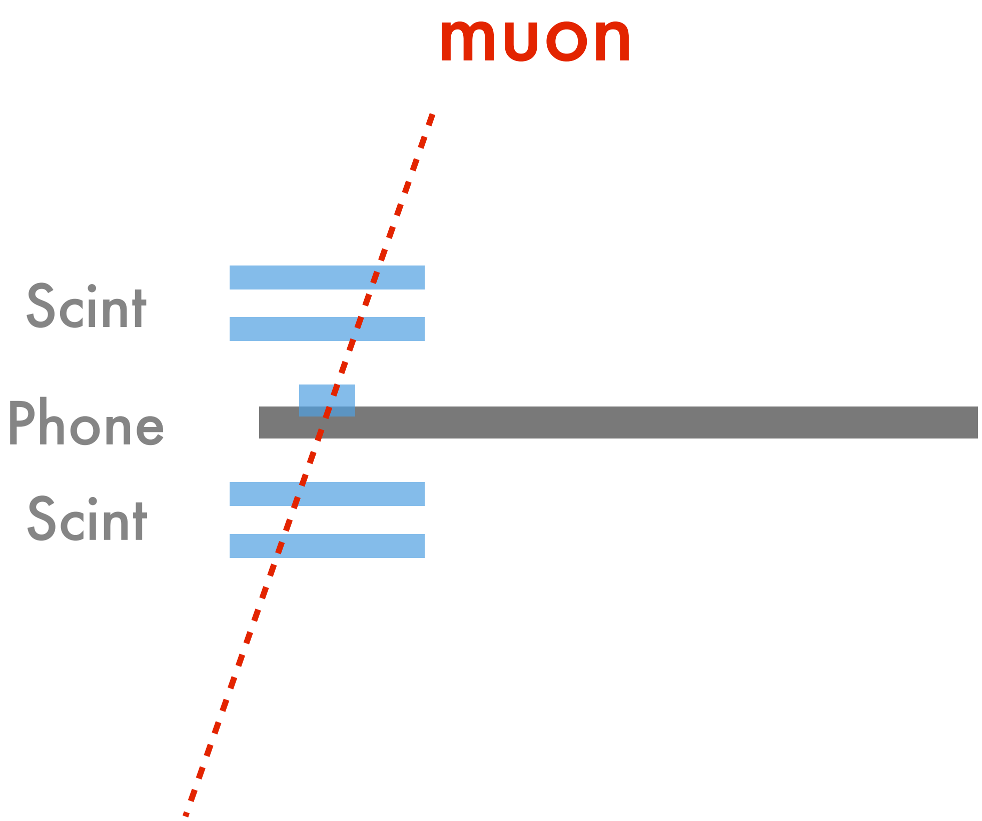
Rate of no-source tails is consistent with cosmic muon flux.

Altitude variation as expected.

The track

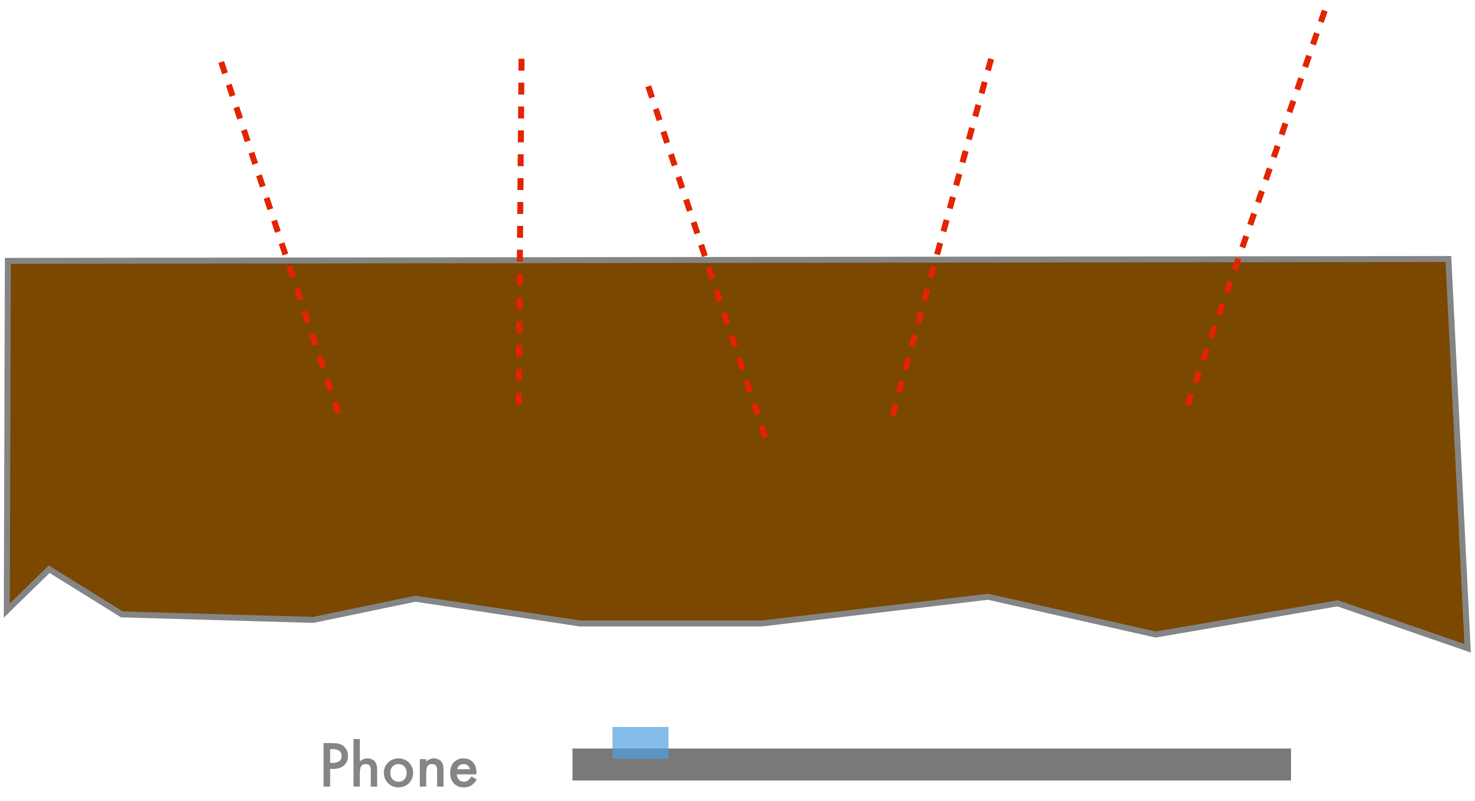

Y
240
220
200
180
160
140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
X

Scintillator tests



In progress at Davis.

Noise measurement



In progress at Gran Sasso.

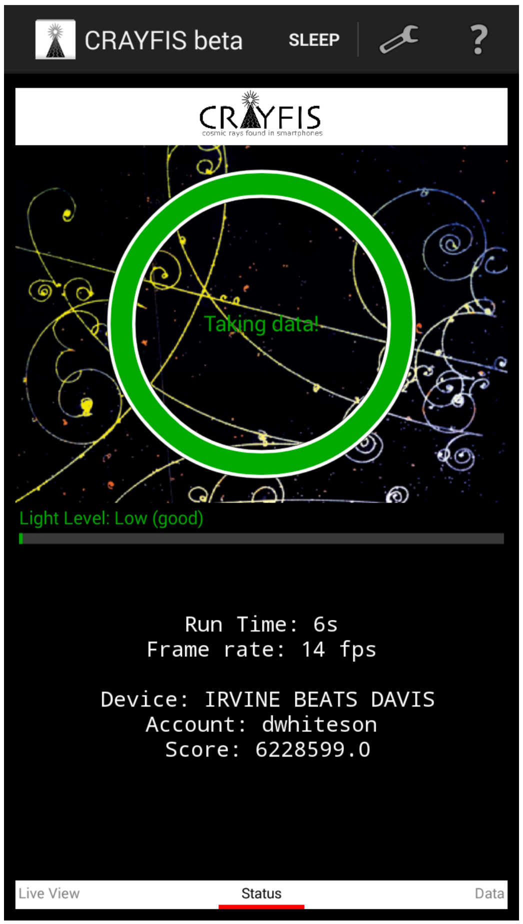
MC model

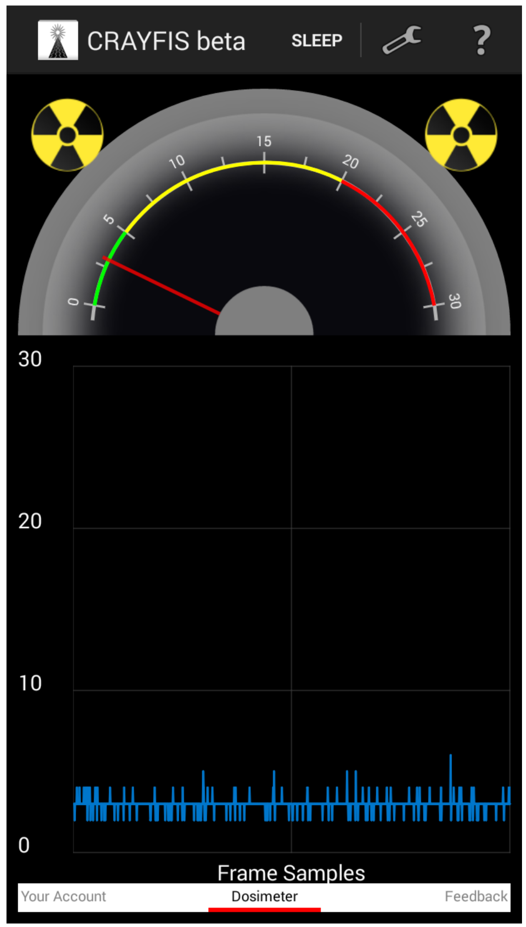
GEANT model of
silicon block

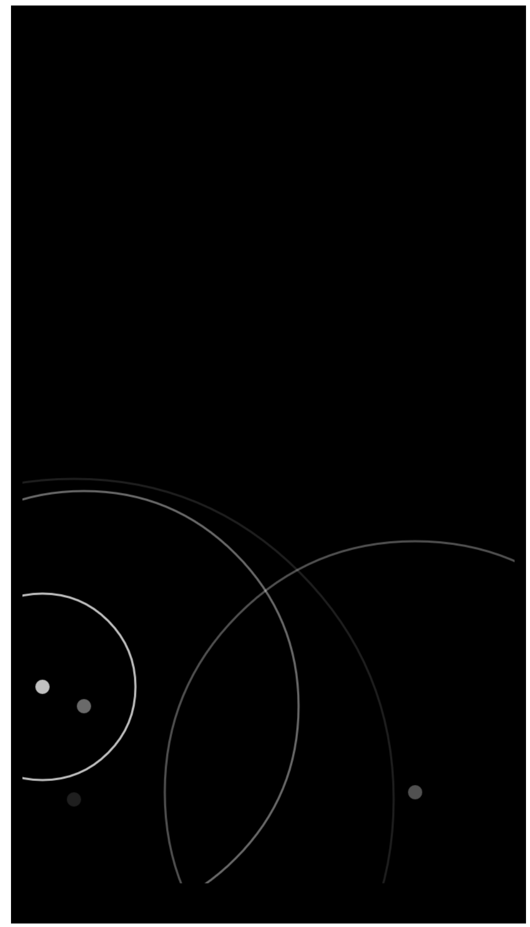
Phone

In progress with Kleinfelder Lab (EE at UCI)

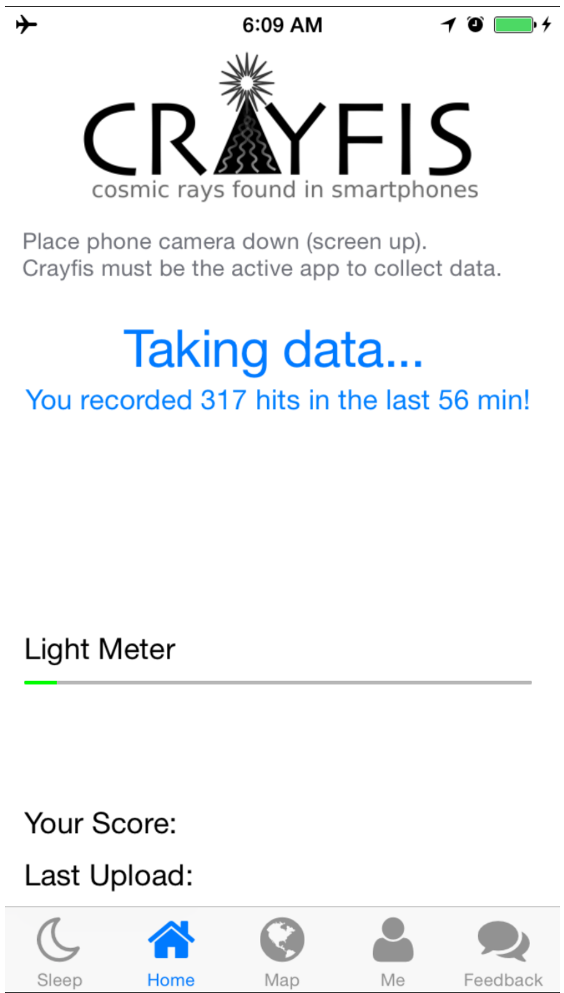
Android App


CRAYFIS beta
SLEEP
CRAYFIS
Taking data!
Light Level: Low (good)
Run Time: 6s
Frame rate: 14 fps
Device: IRVINE BEATS DAVIS
Account: dwhiteson
Score: 6228599.0
Live View
Status
Data

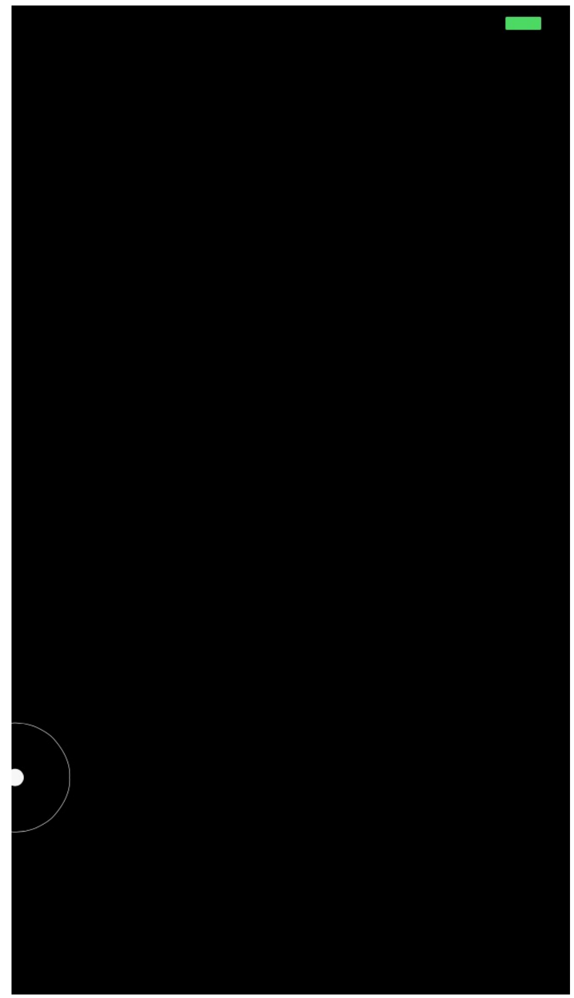

CRAYFIS beta
SLEEP
0
5
10
15
20
25
30
30
20
10
0
Frame Samples
Your Account
Dosimeter
Feedback



iOS app



6:09 AM
CRAYFIS
cosmic rays found in smartphones
Place phone camera down (screen up).
Crayfis must be the active app to collect data.
Taking data...
You recorded 317 hits in the last 56 min!
Light Meter
Your Score:
Last Upload:
Sleep
Home
Map
Me
Feedback



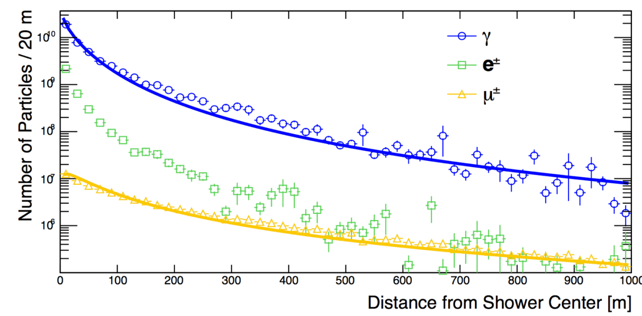
Performance

Overview

Distribution function

Full-simulation with CORSIKA

Fit lateral distribution function (LDF)



Toy simulation

Random distribution of N phones in 1 km^2

Use parametric LDF for true density

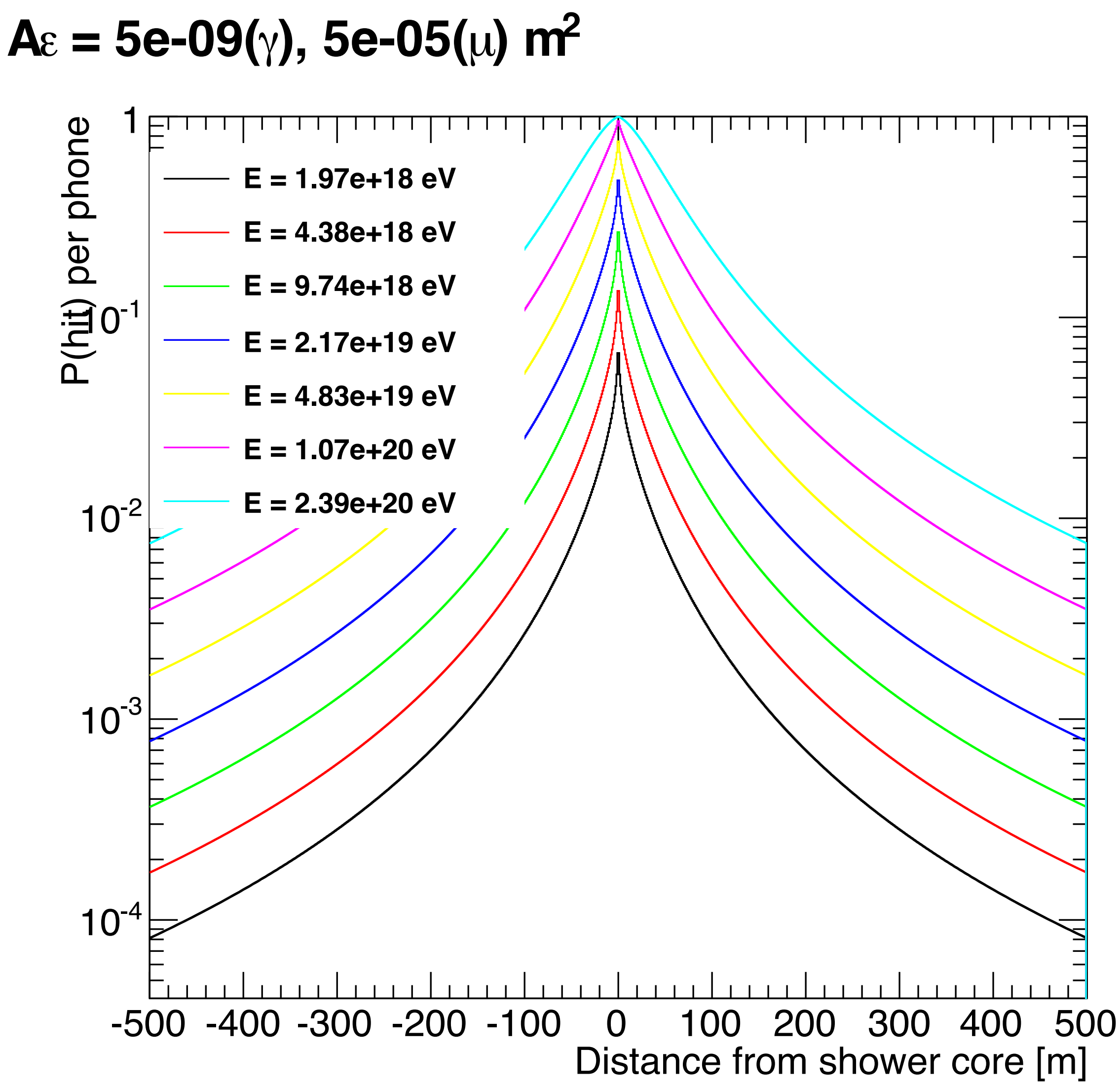
For each phone, prob of a hit is $A\epsilon\cdot\rho(x,y)$

A : sensor area

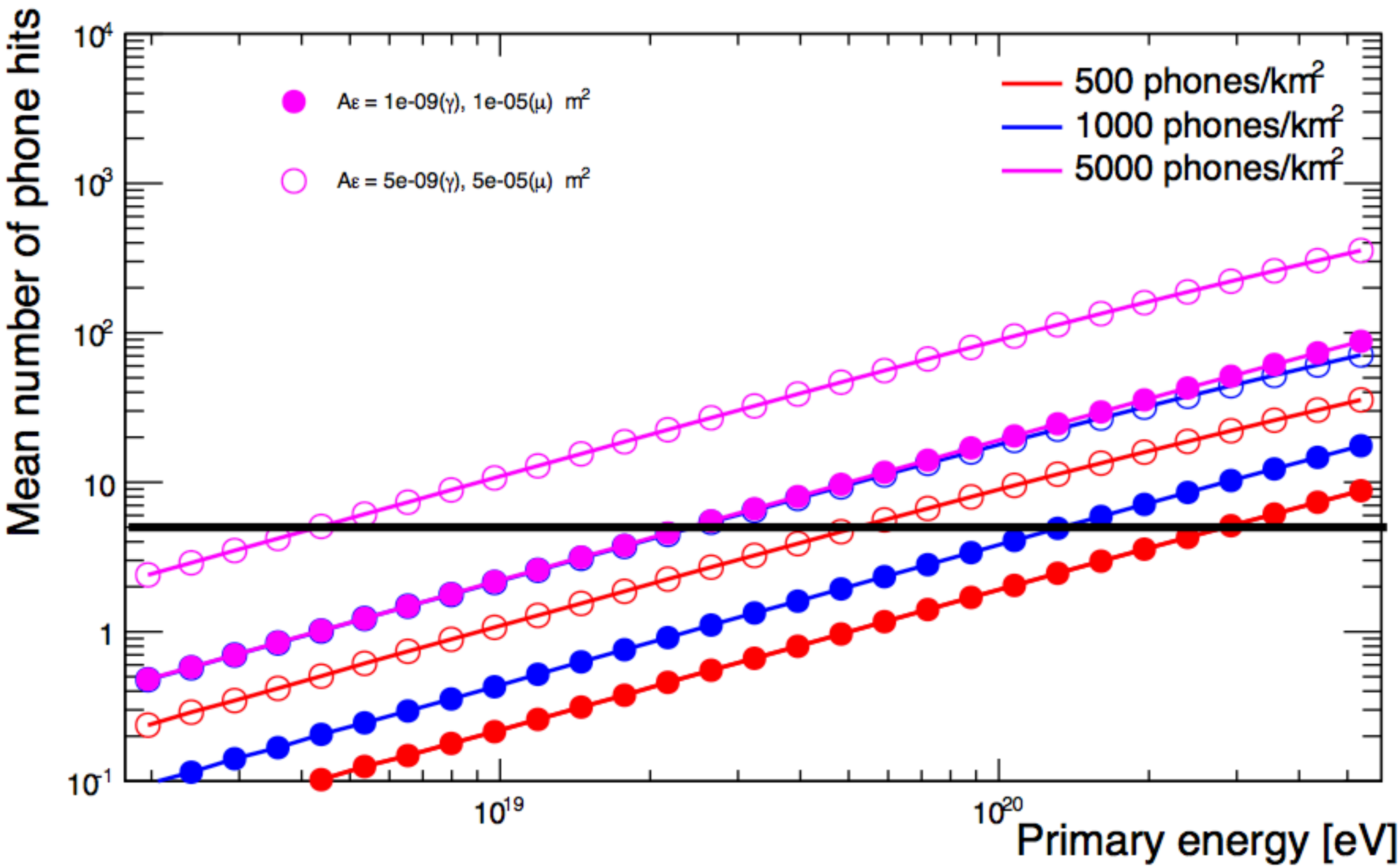
ϵ : efficiency

ρ : particle dens.

Prob to see a hit



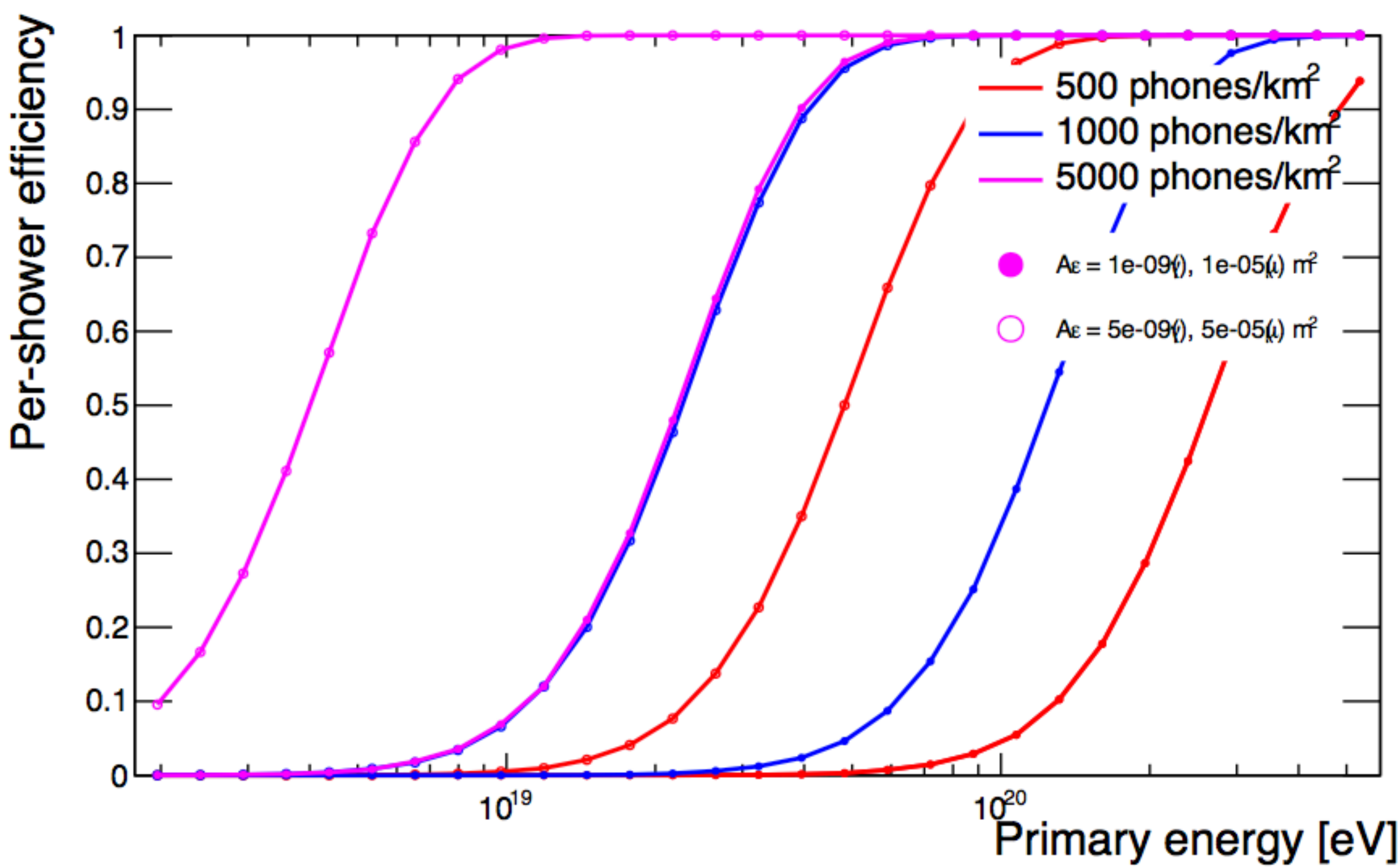
Number of Hits



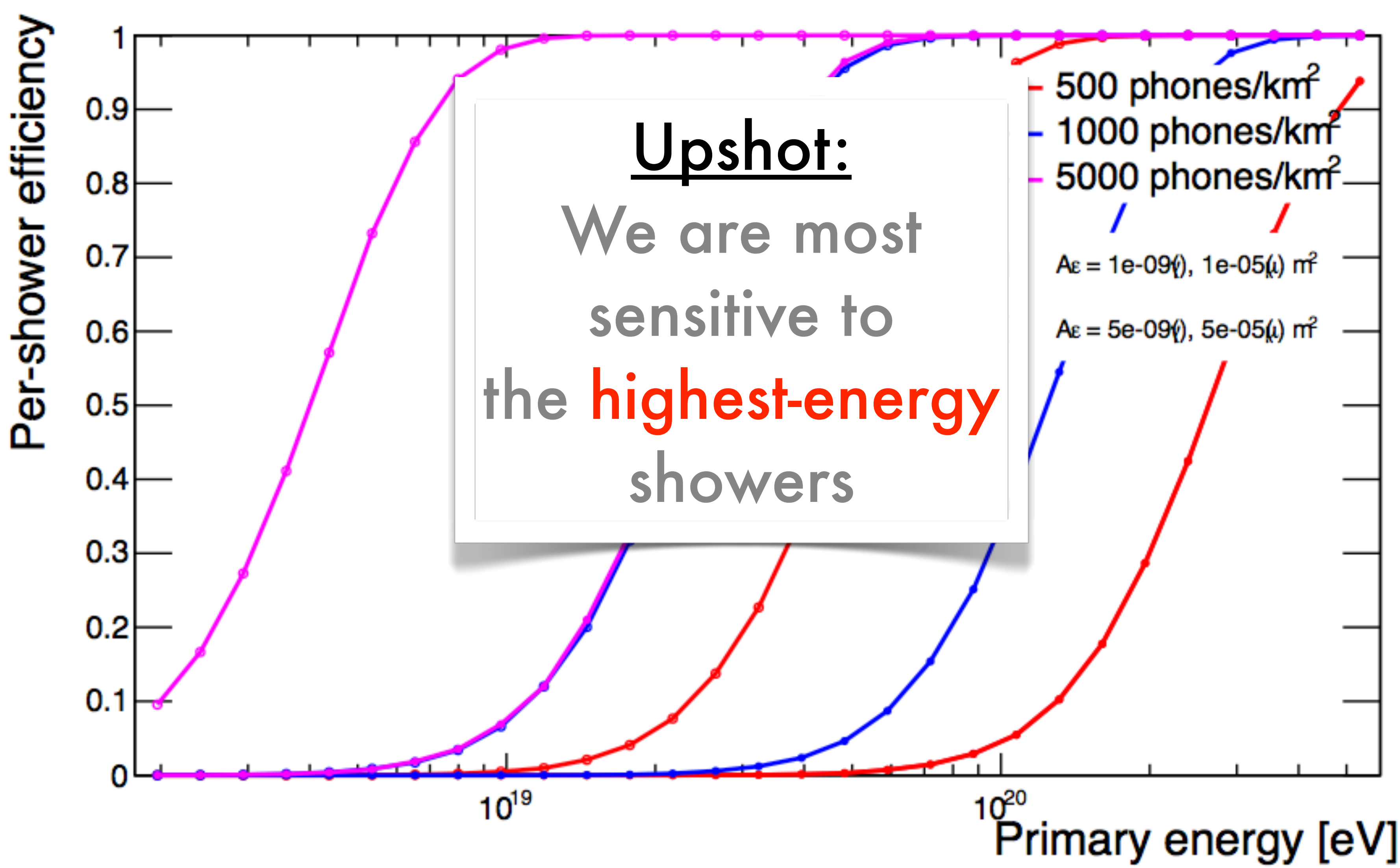
City Densities

Rank	City	Population	Area (km²)	Area (mi²)	Density (/km²)	Density (/mi²)	Country
1	Manila	1,652,171[1]	38.55[2]	14.88	42,857	111,002	Philippines
2	Titagarh	124,213[3]	3.24[4]	1.25	38,337	99,293	India
3	Baranagar	248,466[3]	7.12[4]	2.75	35,220	91,220	India
4	Serampore	197,857[3]	5.88[4]	2.27	33,649	87,151	India
5	Pateros	64,147 [1]	2.10[2]	0.81	30,546	79,114	Philippines
6	Mandaluyong	328,699[1]	11.26[2]	4.35	29,192	75,606	Philippines
7	South Dumdum	392,444[3]	13.54[4]	5.23	28,984	75,069	India
8	Kamarhati	314,507[3]	10.96[4]	4.23	28,696	74,323	India
9	Caloocan	1,489,040[1]	53.34[2]	20.6	27,916	72,302	Philippines
10	Levallois-Perret	63,436[5]	2.4[5]	0.93	26,432	68,458	France
11	Le Pré-Saint-Gervais	18,121[6]	0.7[6]	0.27	25,887	67,047	France
12	Neapoli	30,279[7]	1.17[7]	0.45	25,879	67,027	Greece
13	Chennai	4,681,087[8]	181.06[9]	69.91	25,854	66,961	India
14	Vincennes	48,689[10]	1.9[10]	0.733	25,626	66,371	France
15	Delhi	11,007,835[8]	431.09[11]	166.4	25,535	66,135	India
16	Saint-Mandé	22,627[12]	0.9[12]	0.35	25,141	65,115	France
17	Bally	291,972[3]	11.81[13]	4.56	24,722	64,031	India
18	Kolkata	4,486,679[8]	185[14]	71.4	24,252	62,813	India
19	Saint-Josse-ten-Noode	27,548[15]	1.14[16]	0.44	24,165	62,404	Belgium
20	Navotas	249,131[1]	10.77[2]	4.16	23,132	59,911	Philippines

Efficiency


Per-shower efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{19}
10^{20}
Primary energy [eV]
500 phones/km^2
1000 phones/km^2
5000 phones/km^2
Aε = 1e-09(γ), 1e-05(μ) m^2
Aε = 5e-09(γ), 5e-05(μ) m^2

Efficiency



Upshot:

We are most sensitive to the highest-energy showers

Reconstruction

Maths

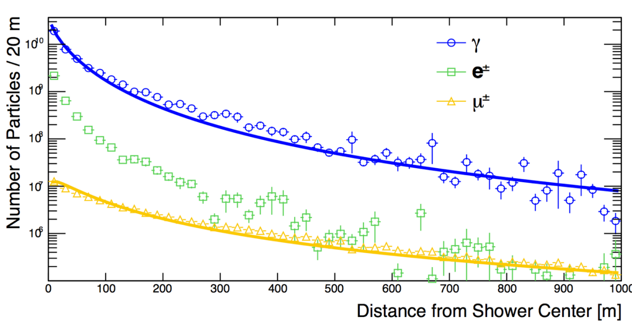
$$\vec{s} : (r, \theta, \phi) = (s, \theta_s, \phi_s) \Rightarrow (x, y, z) = s \cdot (\sin\theta_s \cos\phi_s,\ \sin\theta_s\ \sin\phi_s,\ \cos\theta_s)$$

$$\vec{R} : (r, \theta, \phi) = (R, \pi/2, \phi_d) \Rightarrow (x, y, z) = R \cdot (\cos\phi_d,\ \sin\phi_d,\ 0)$$

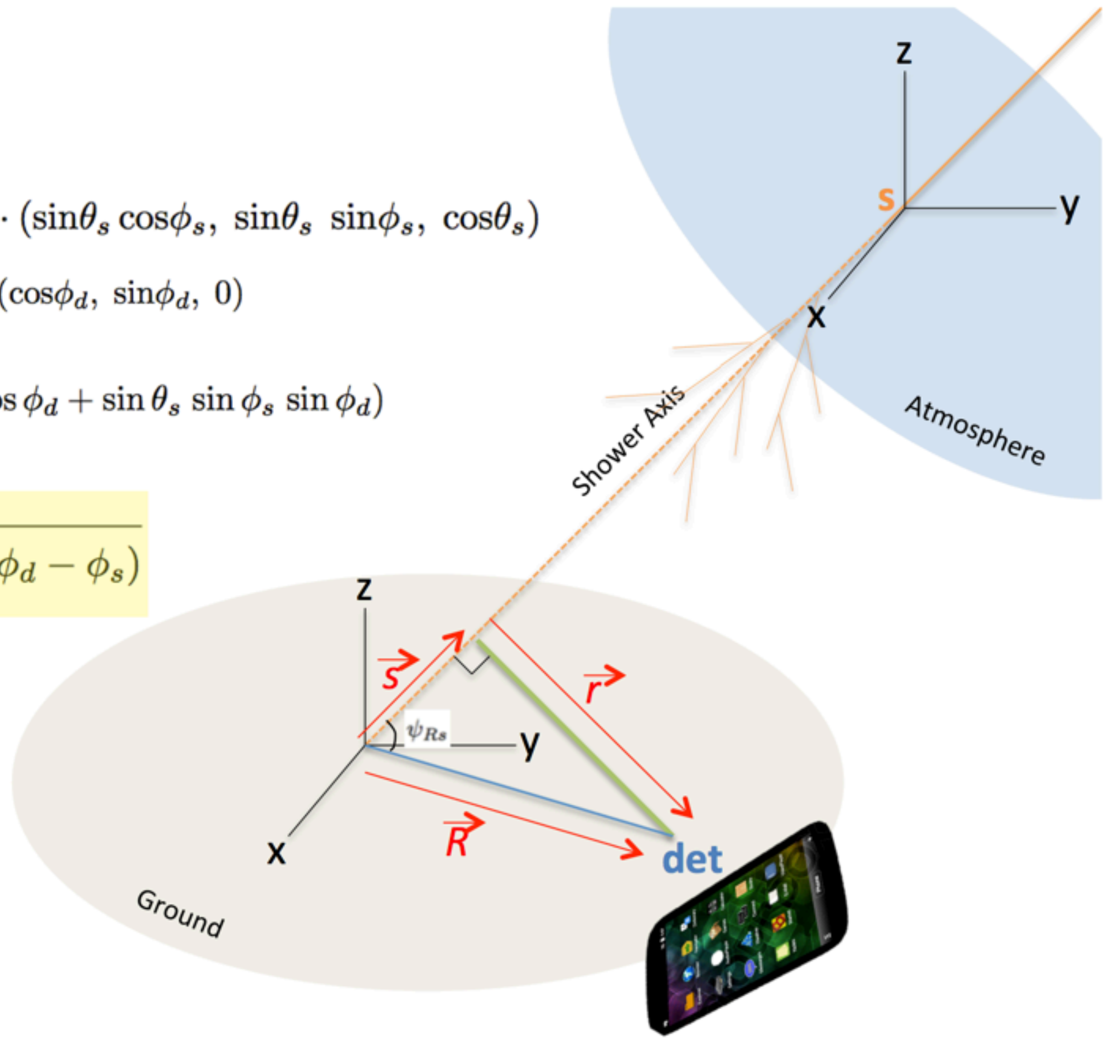
$$s = R\cos\psi_{Rs} = R\frac{\vec{R}\cdot\vec{s}}{R\,s} = R(\sin\theta_s\,\cos\phi_s\,\cos\phi_d + \sin\theta_s\,\sin\phi_s\,\sin\phi_d)$$

$$s = R\sin\theta_s\,\cos(\phi_d - \phi_s)$$

$$r = \sqrt{R^2 - s^2} = R\sqrt{1 - \sin^2\theta_s\,\cos^2(\phi_d - \phi_s)}$$

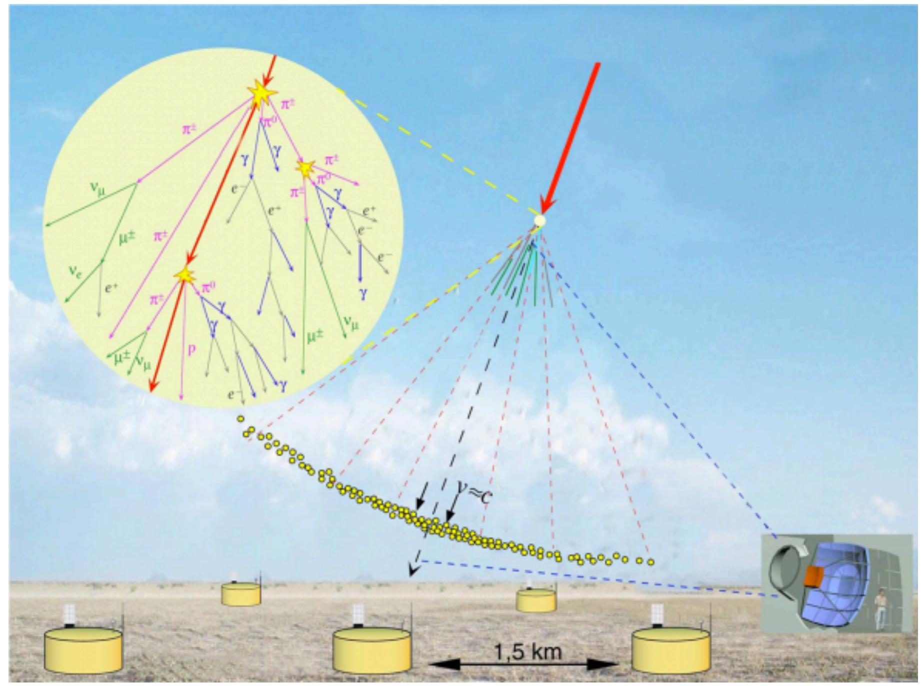


r

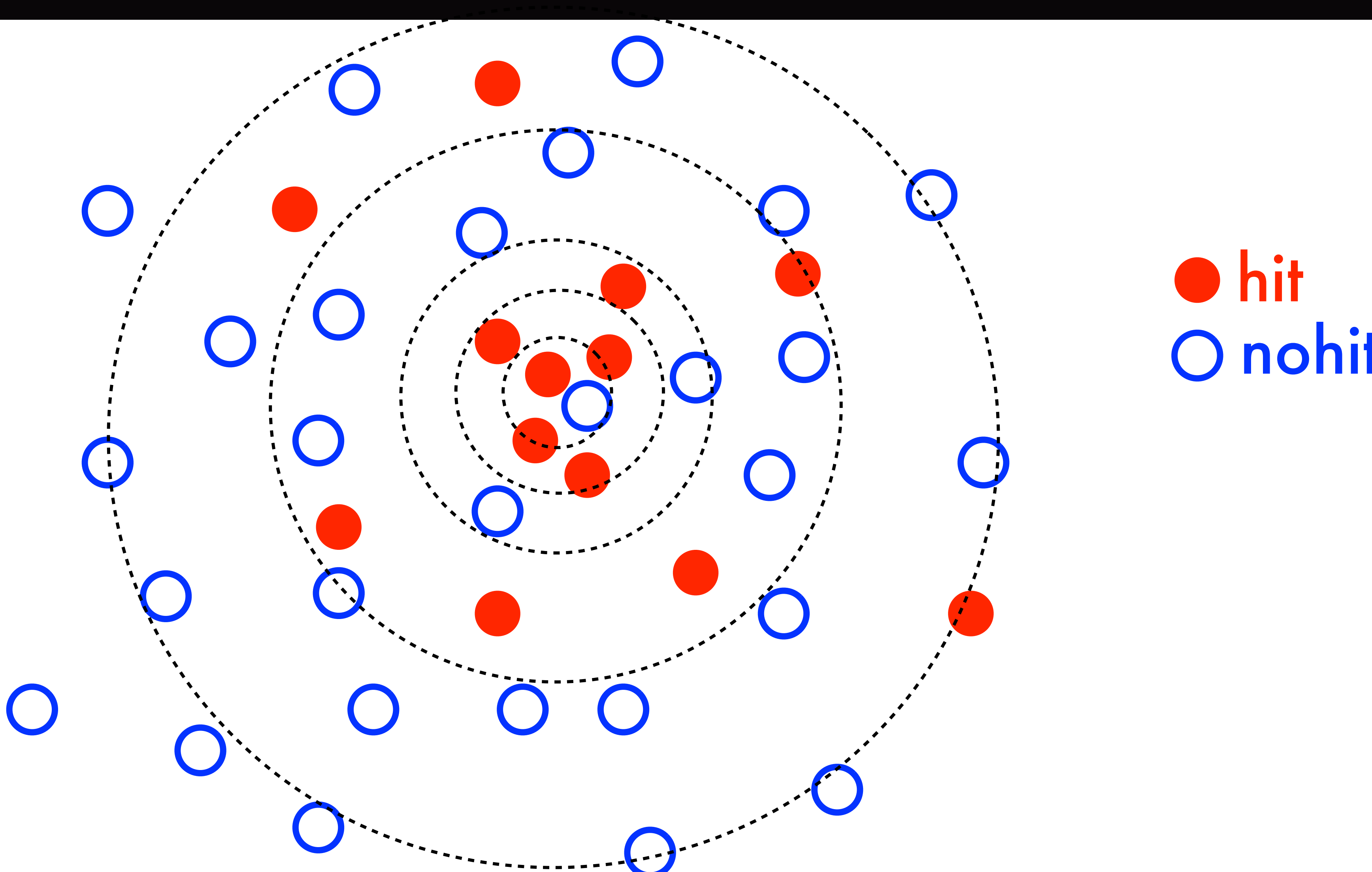


Reconstruction

Auger has
a regular
grid and
pico-second
timing

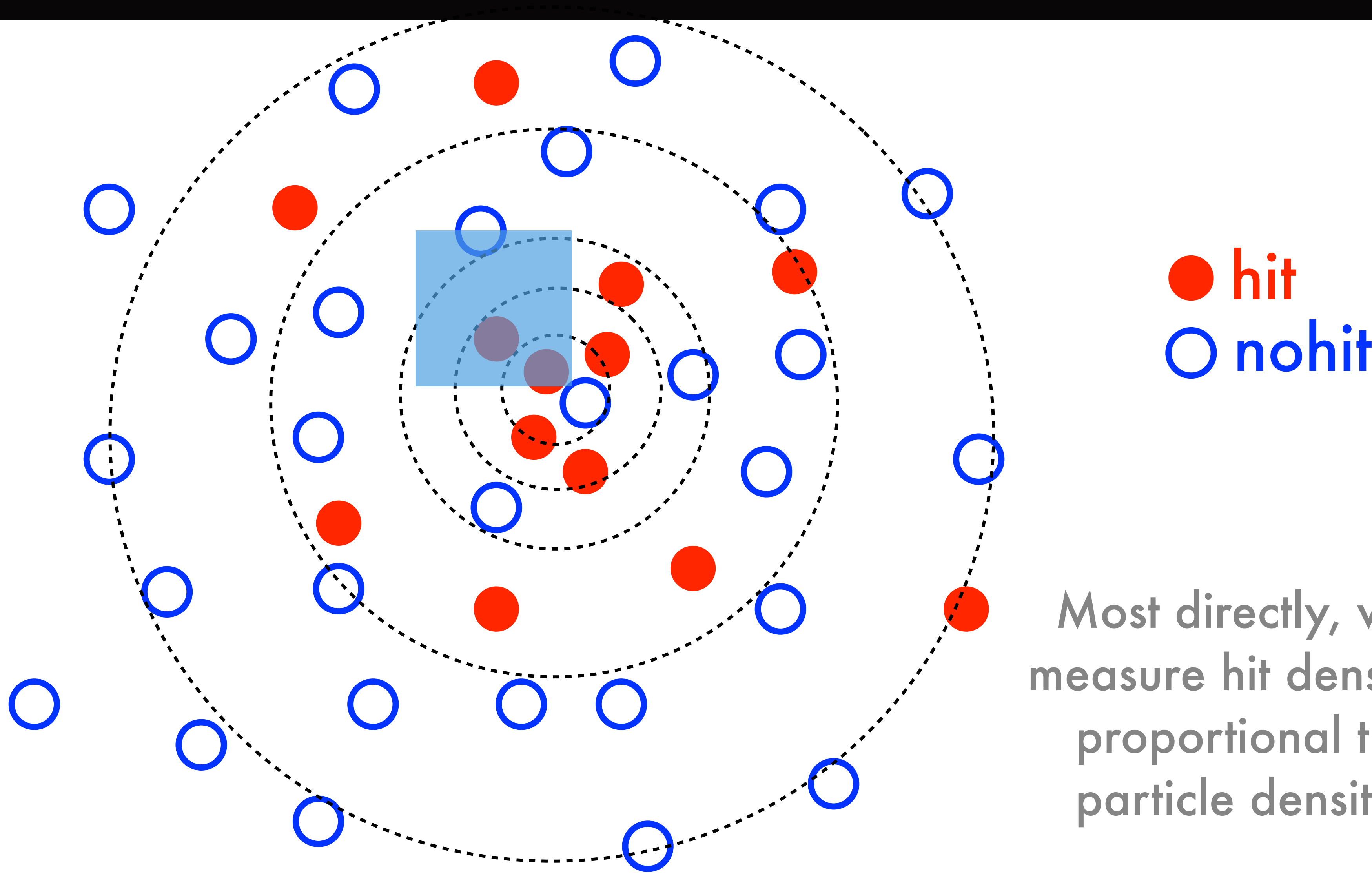


Reconstruction



We have an irregular network, and ~100 ms timing

Hit Density



Most directly, we measure hit density, proportional to particle density

Likelihood

nohit hit

$$L(N,\theta,\phi) = \prod_i P_0(x_i, y_i) \prod_j P_1(x_j, y_j)$$

$$P_0(x,y) = e^{-A\epsilon\cdot\boldsymbol{\rho}(x,y)-\eta},$$

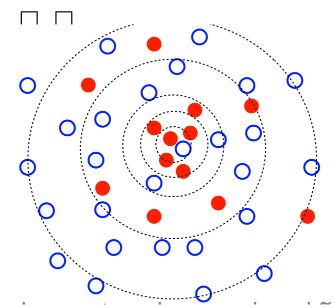
$$P_1(x,y) = 1.0 - e^{-A\epsilon\cdot\boldsymbol{\rho}(x,y)-\eta}.$$

A : sensor area

ϵ : efficiency

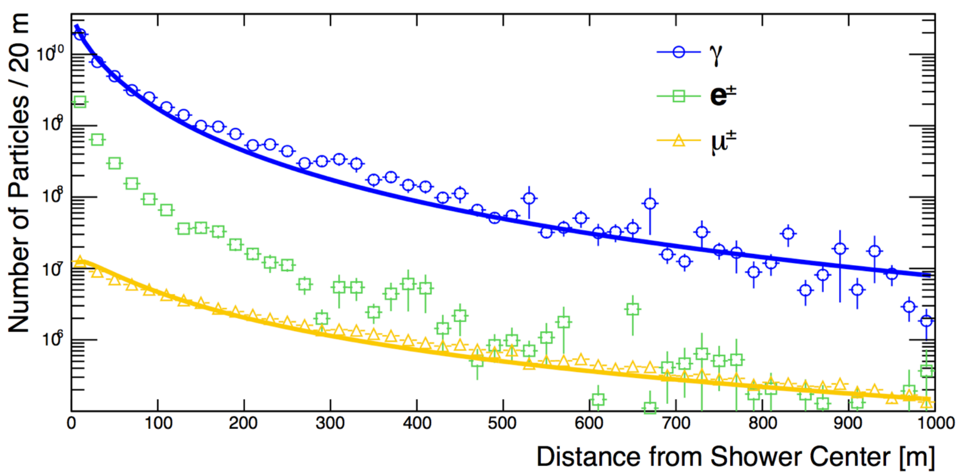
$\boldsymbol{\rho}$: particle dens

η : noise



Density

$$\rho(N_i, r, s) = \frac{N_i}{2\pi r_M^2} \left(\frac{r}{r_M}\right)^{(s-2)} \left(1 + \frac{r}{r_M}\right)^{(s-4.5)} \times \left(\frac{\Gamma(4.5 - s)}{\Gamma(s)\Gamma(4.5 - 2s)}\right) [\mathrm{m}^{-2}]$$



r : distance to vector of initial particle

N_i : number of particles in shower

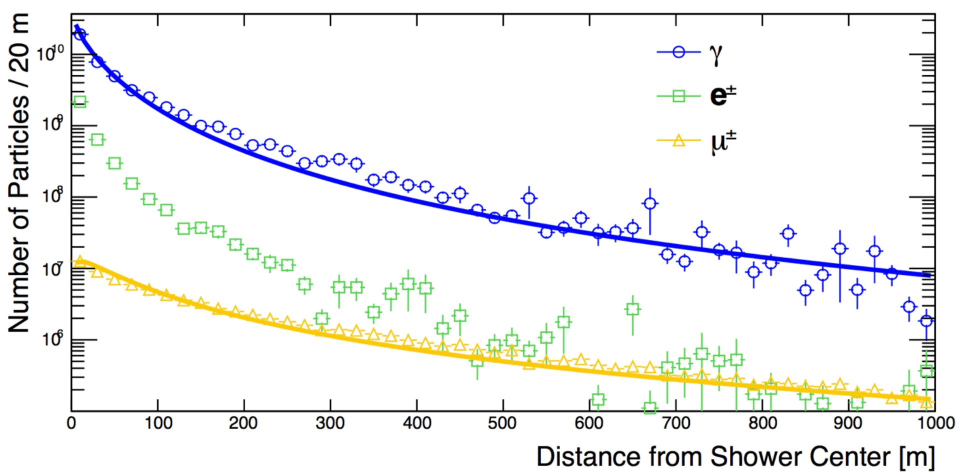
s : shower age (s=1 is max)

r_M : Moliere radius in air

Density

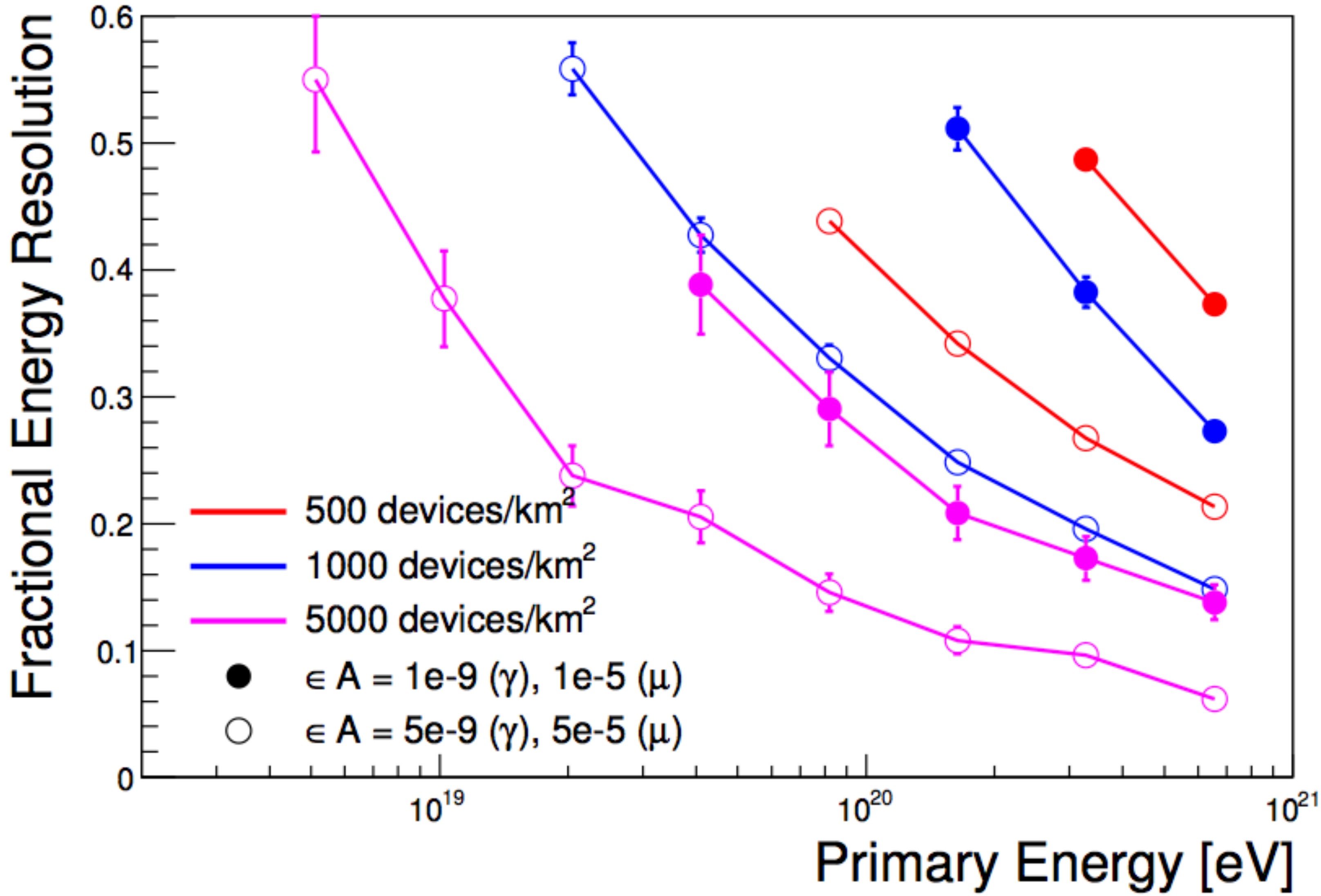
Proportional to principal particle initial energy.

$$\rho(N_i, r, s) = \frac{N_i}{2\pi r_M^2}\left(\frac{r}{r_M}\right)^{(s-2)}\left(1+\frac{r}{r_M}\right)^{(s-4.5)} \times \left(\frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)}\right)[\mathrm{m}^{-2}]$$



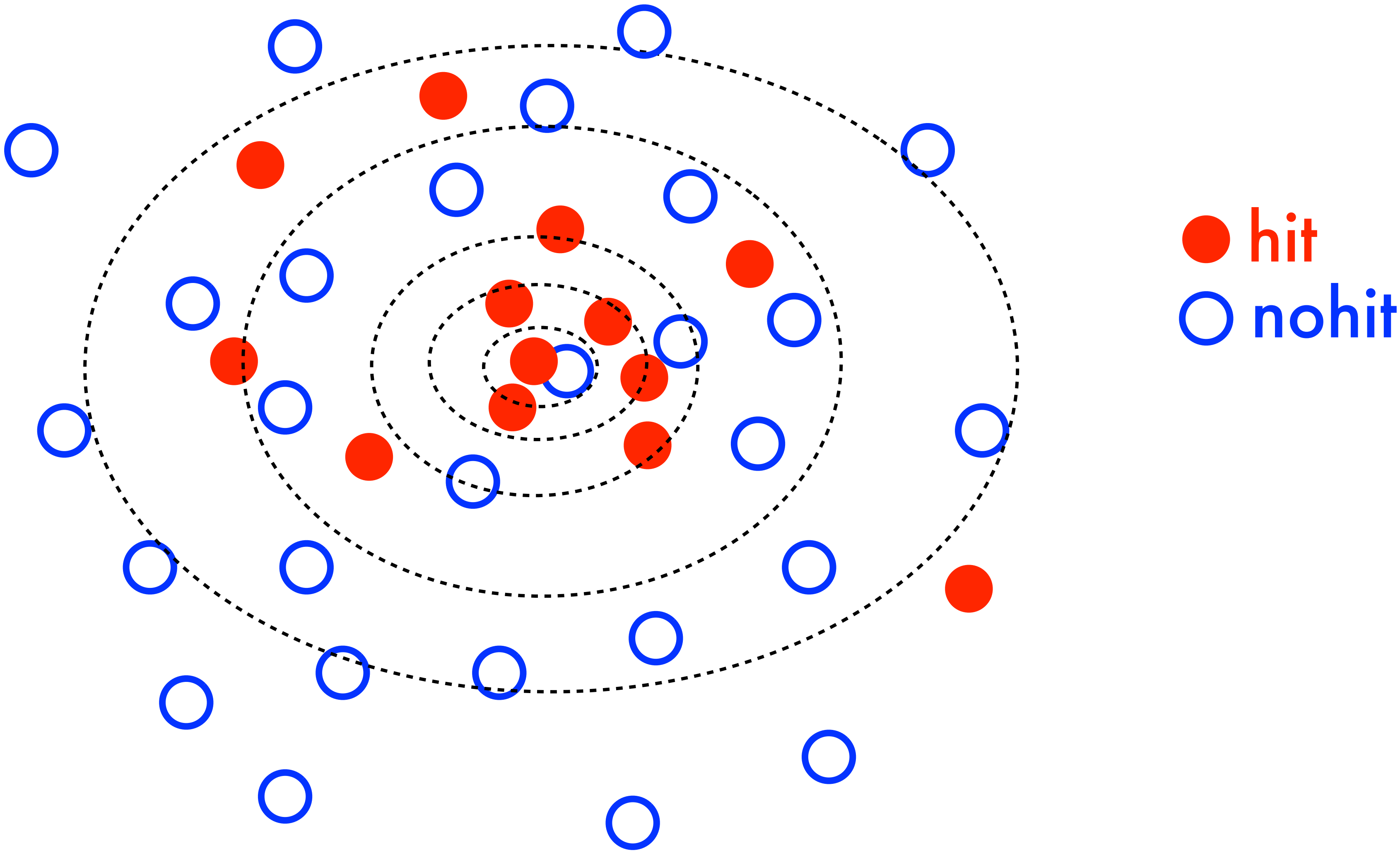
r : distance to vector of initial particle
N_i : number of particles in shower
s : shower age (s=1 is max)
r_M : Moliere radius in air

Resolution



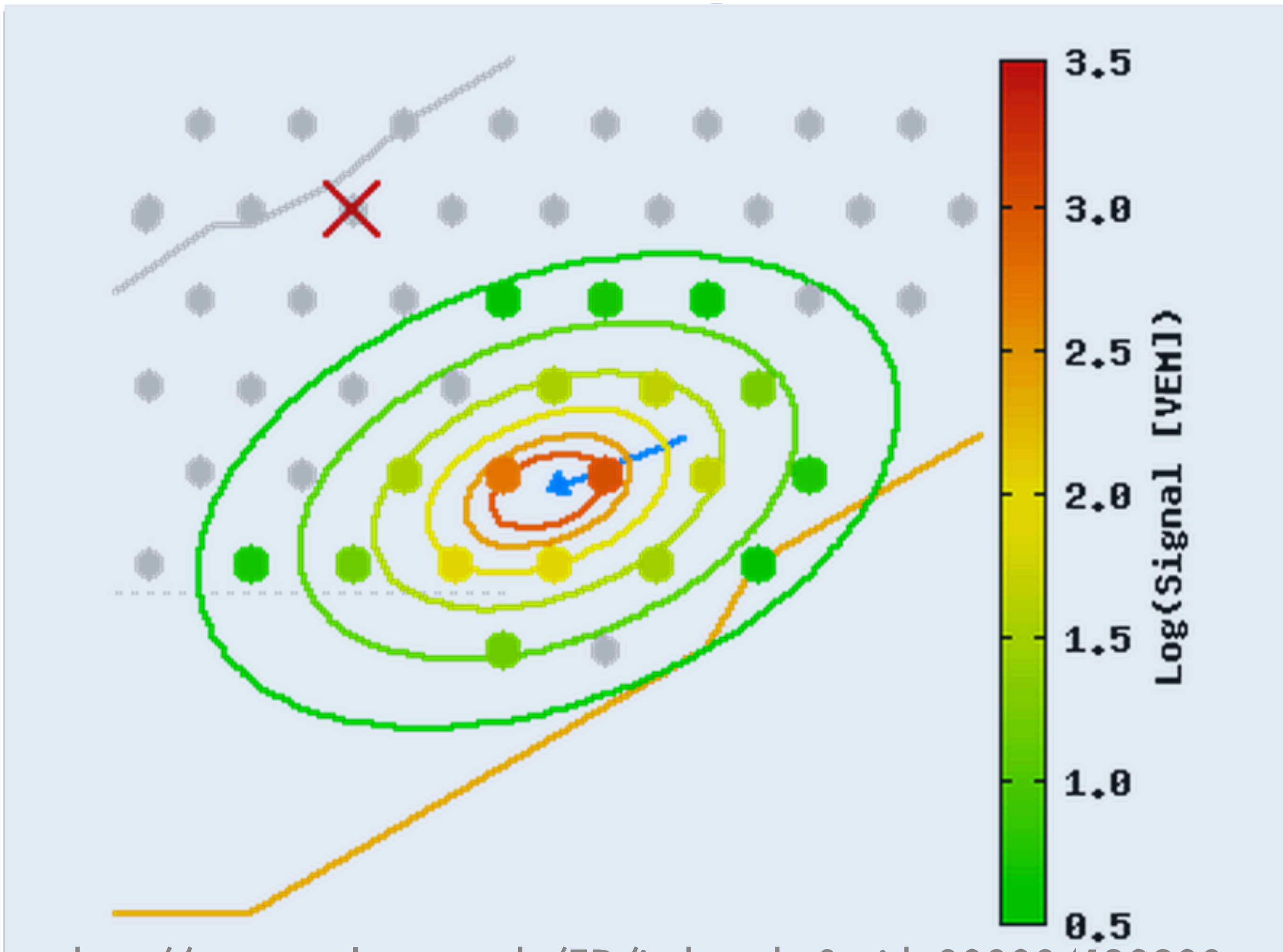
Fractional Energy Resolution
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{19}
10^{20}
10^{21}
Primary Energy [eV]
500 devices/km^2
1000 devices/km^2
5000 devices/km^2
ϵA = 1e-9 (γ), 1e-5 (μ)
ϵA = 5e-9 (γ), 5e-5 (μ)

Angles



Eccentricity gives theta, major axis gives phi

Angles

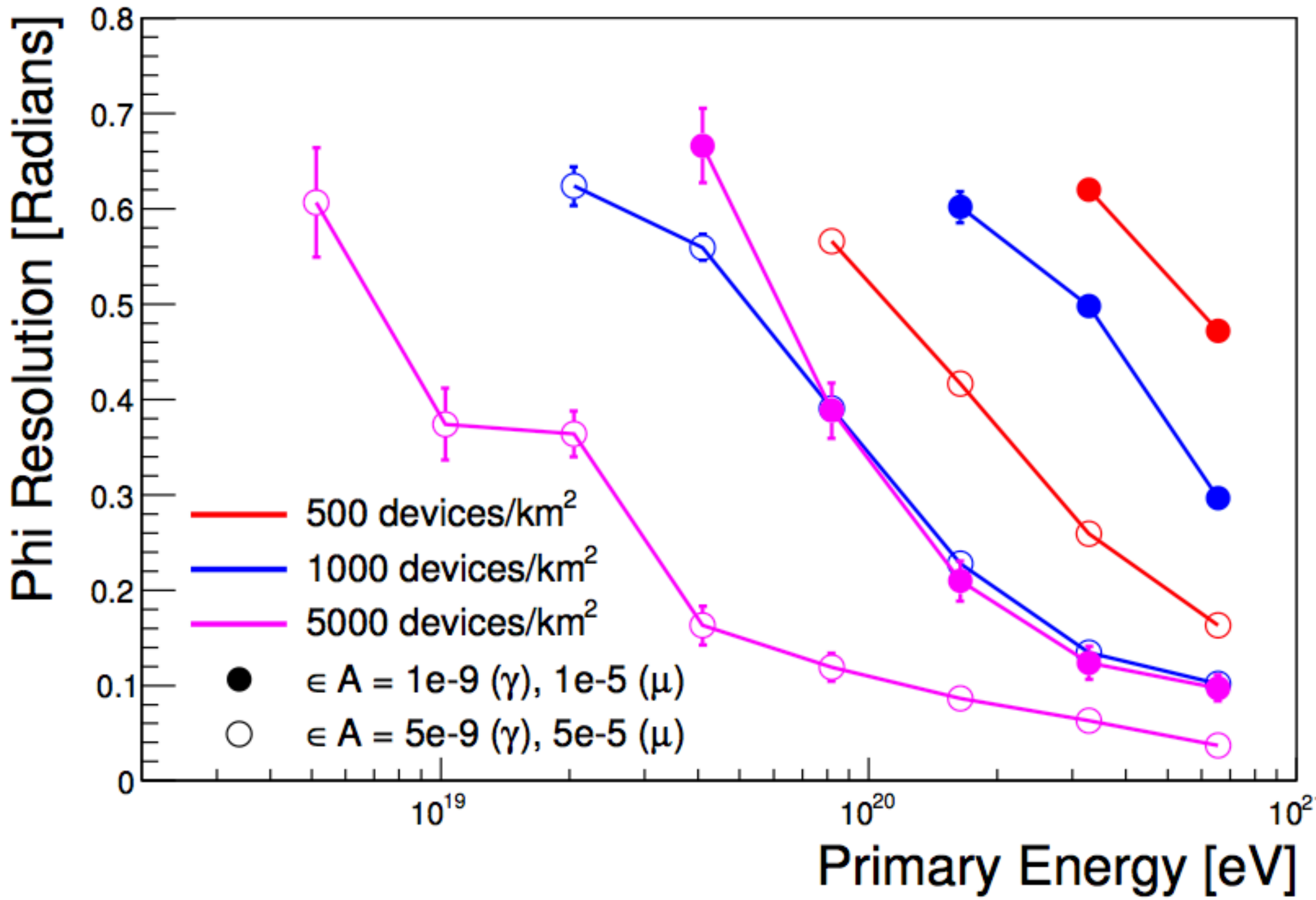


● hit
○ nohit

http://auger.colostate.edu/ED/index.php?evid=000004128900

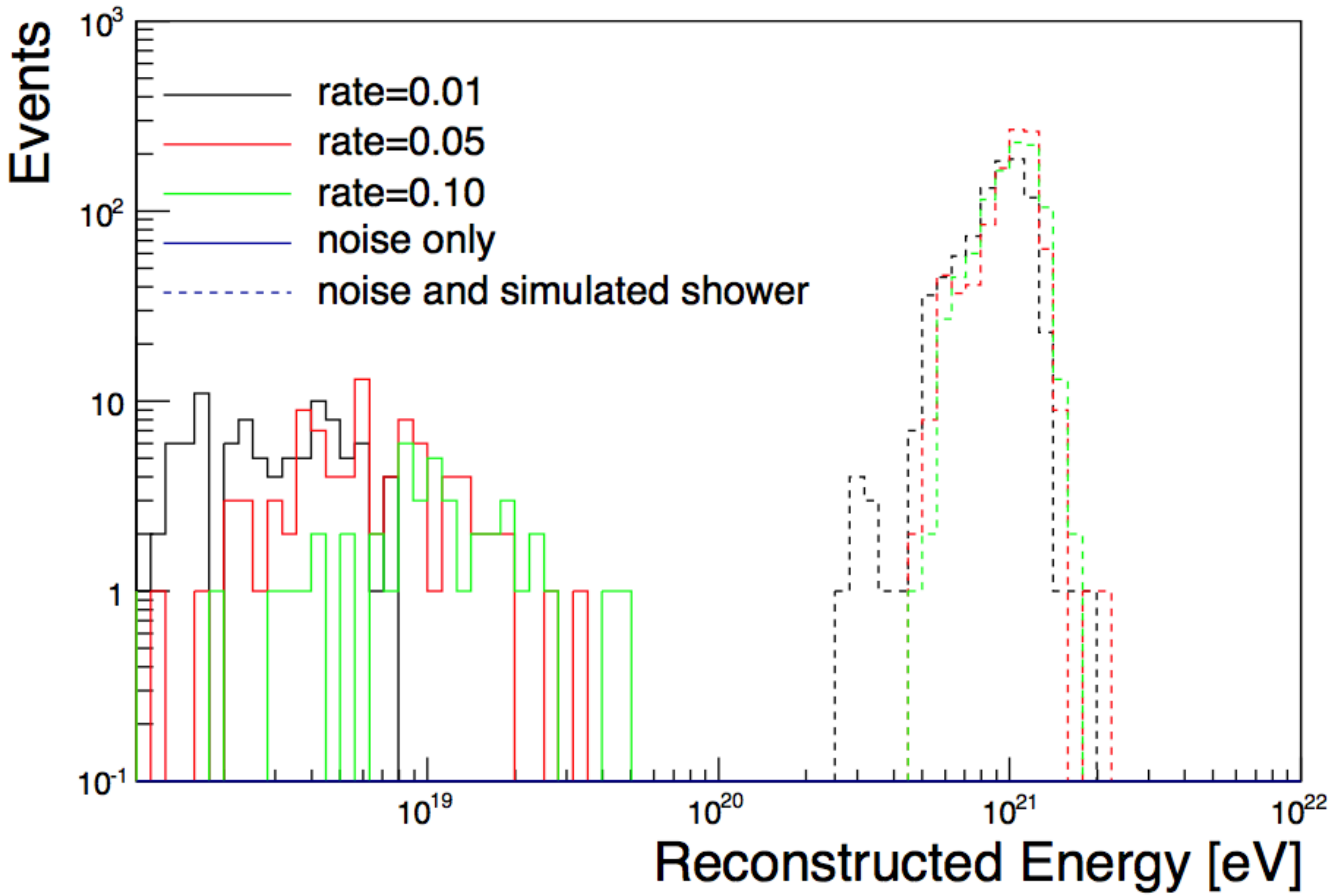
Eccentricity gives theta, major axis gives phi

Resolution



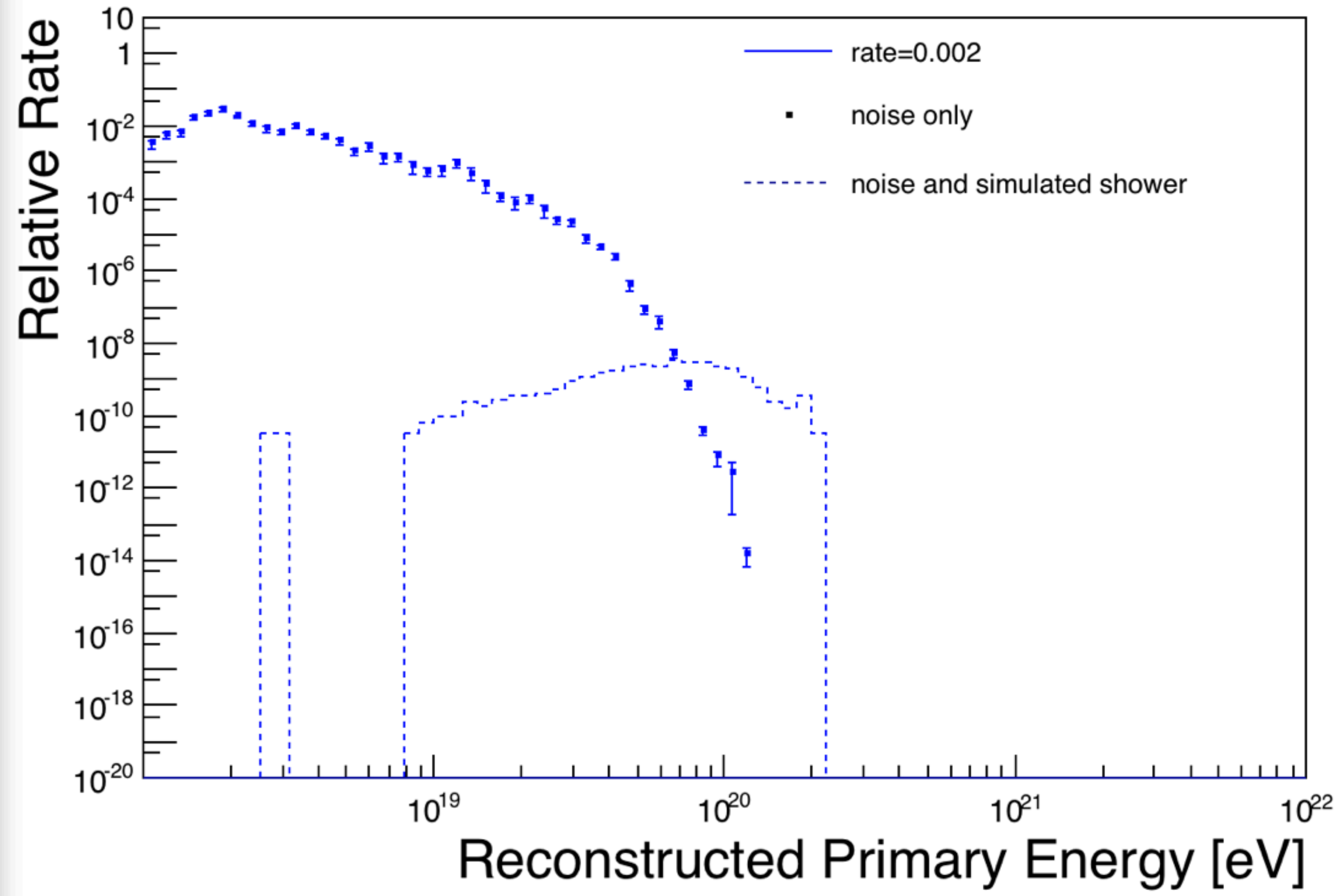
Phi Resolution [Radians]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{19}
10^{20}
10^{21}
Primary Energy [eV]
500 devices/km^2
1000 devices/km^2
5000 devices/km^2
ϵ A = 1e-9 (γ), 1e-5 (μ)
ϵ A = 5e-9 (γ), 5e-5 (μ)

Noise?



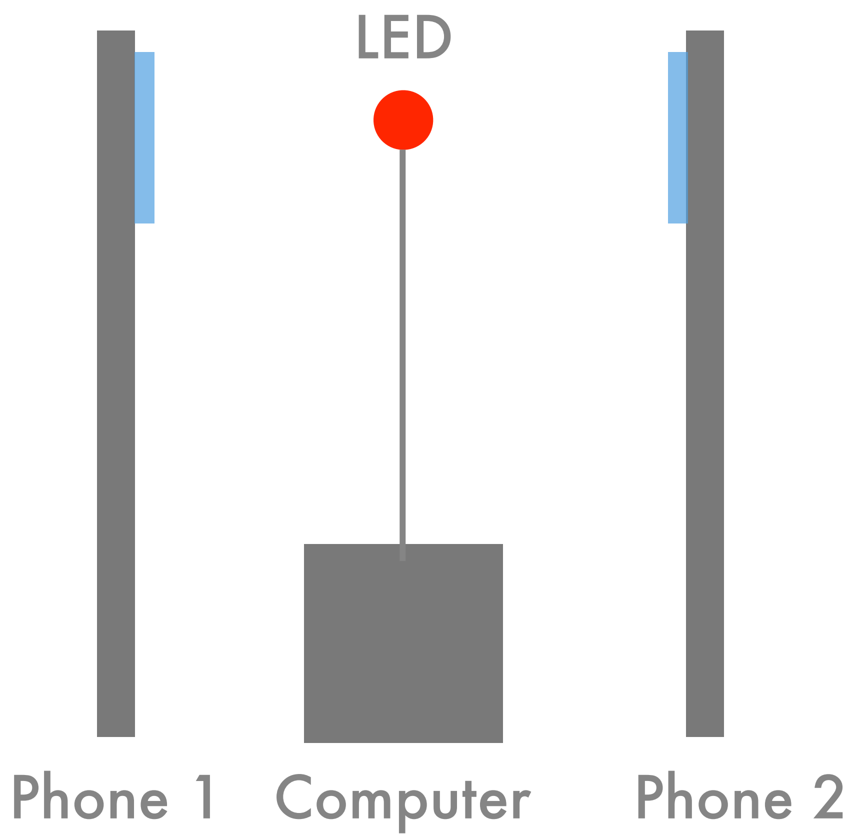
Events
rate=0.01
rate=0.05
rate=0.10
noise only
noise and simulated shower
10^{3}
10^{2}
10
1
10^{-1}
10^{19}
10^{20}
10^{21}
10^{22}
Reconstructed Energy [eV]

Noise rates



Relative Rate
10
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{19}
10^{20}
10^{21}
10^{22}
Reconstructed Primary Energy [eV]
rate=0.002
noise only
noise and simulated shower

Timing

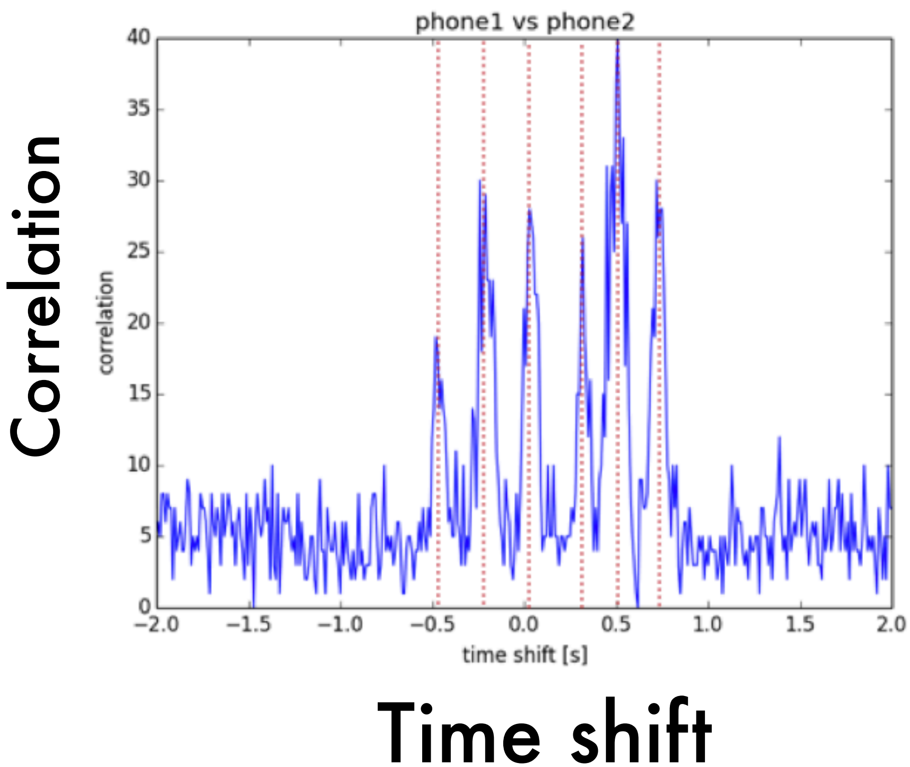


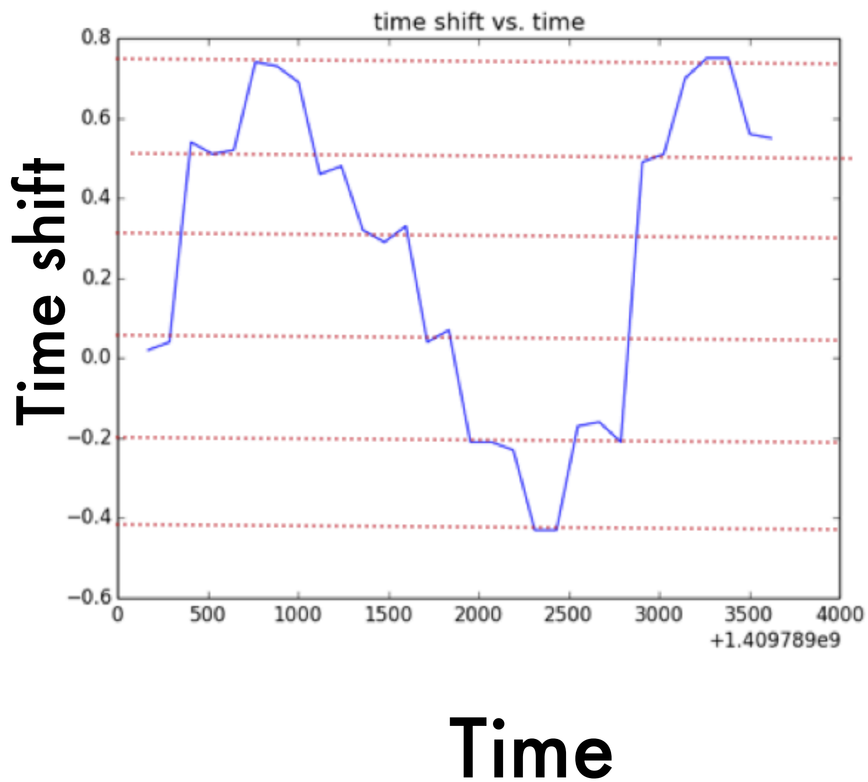
Timing test

Random blinking LED

Measure capture time
on two phones.

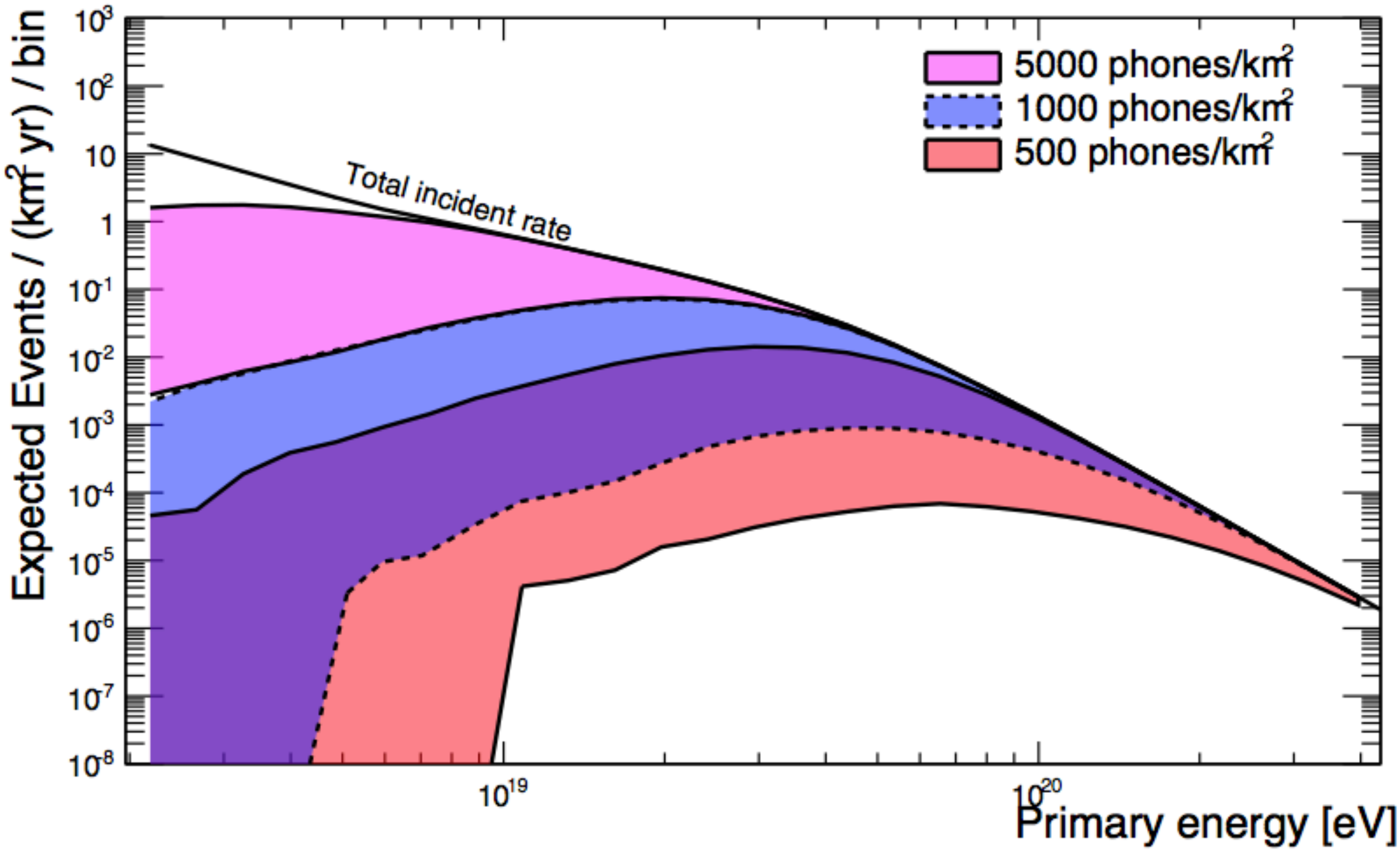
Timing





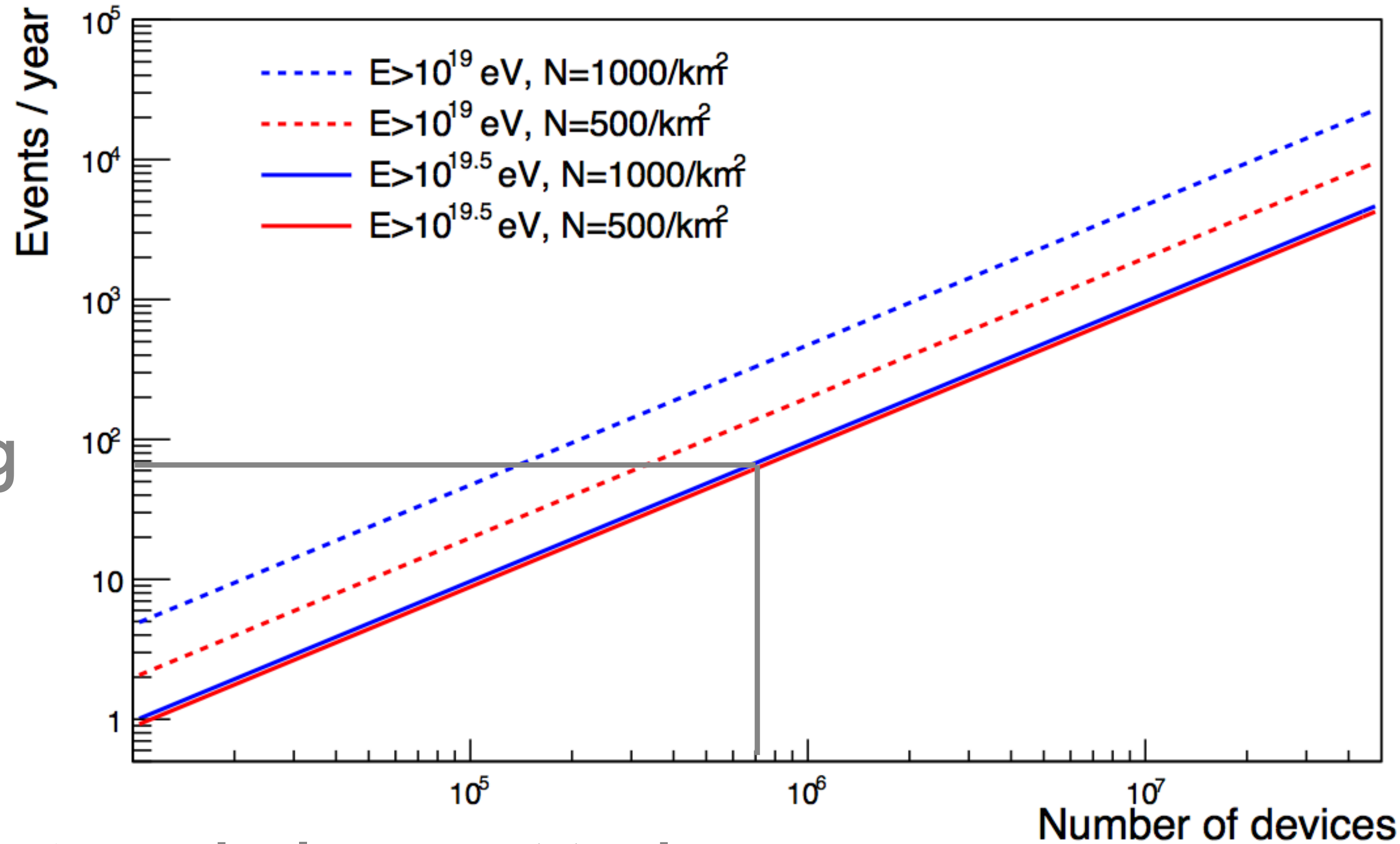
Naive timing subject to
NTP update unpredictability

Power in 1km^2



How many do we need?

Auger observing power



Need almost **1M** phones

Paper

Cornell University Library

arXiv.org > astro-ph > arXiv:1410.2895

Astrophysics > Instrumentation and Methods for Astrophysics

Observing Ultra-High Energy Cosmic Rays with Smartphones

Daniel Whiteson, Michael Mulhearn, Chase Shimmin, Kyle Brodie, Dustin Burns

(Submitted on 10 Oct 2014)

We propose a novel approach for observing cosmic rays at ultra-high energy ($> 10^{18}$~eV) by repurposing the existing network of smartphones as a ground detector array. Extensive air showers generated by cosmic rays produce muons and high-energy photons, which can be detected by the CMOS sensors of smartphone cameras. The small size and low efficiency of each sensor is compensated by the large number of active phones. We show that if user adoption targets are met, such a network will have significant observing power at the highest energies.

CRAYFIS

cosmic rays found in smartphones

Whiteson
Shimmin
Strong
Brodie
Goddard
Porter
Sandy

NYU

Cranmer

Яндекс
Yandex

Ustyuzhanin
+2 masters st.

UCDAVIS
UNIVERSITY OF CALIFORNIA

Mulhearn
Burns
Buonacarsi

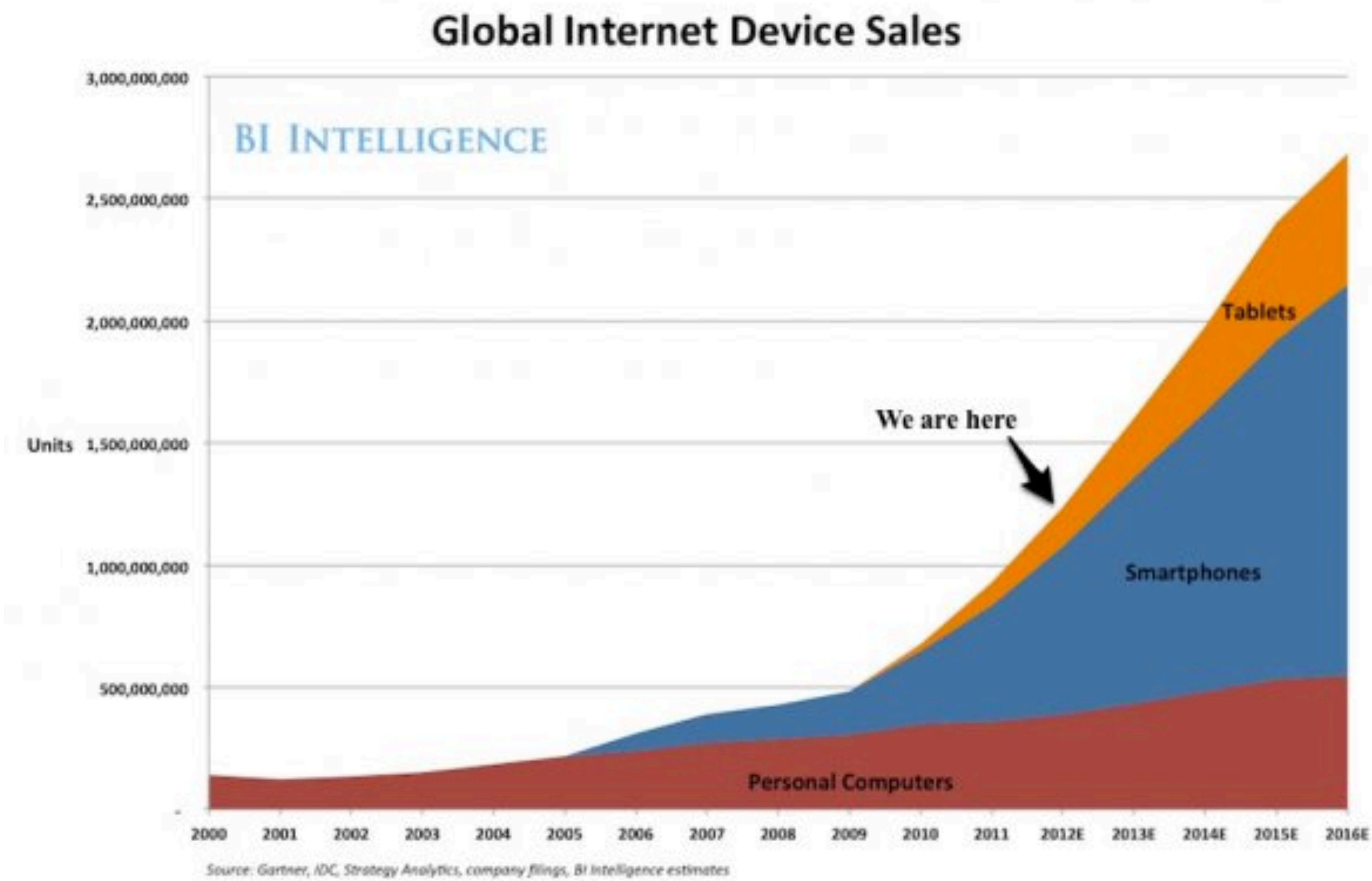
NAOC

Deng

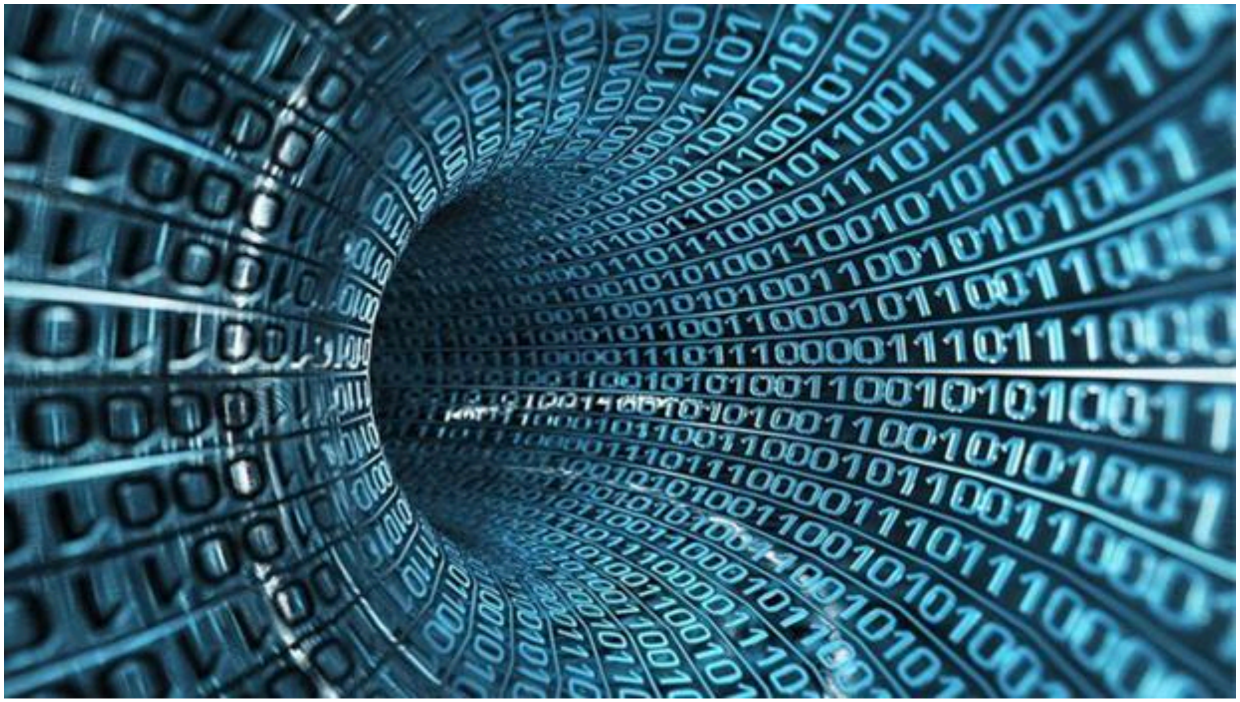
powered by amazon web services

Users

Is 1M reasonable?



Challenge: big data!



DigitalOcean

50k devices

500kb/sec

250 simul. connections

$1000/month

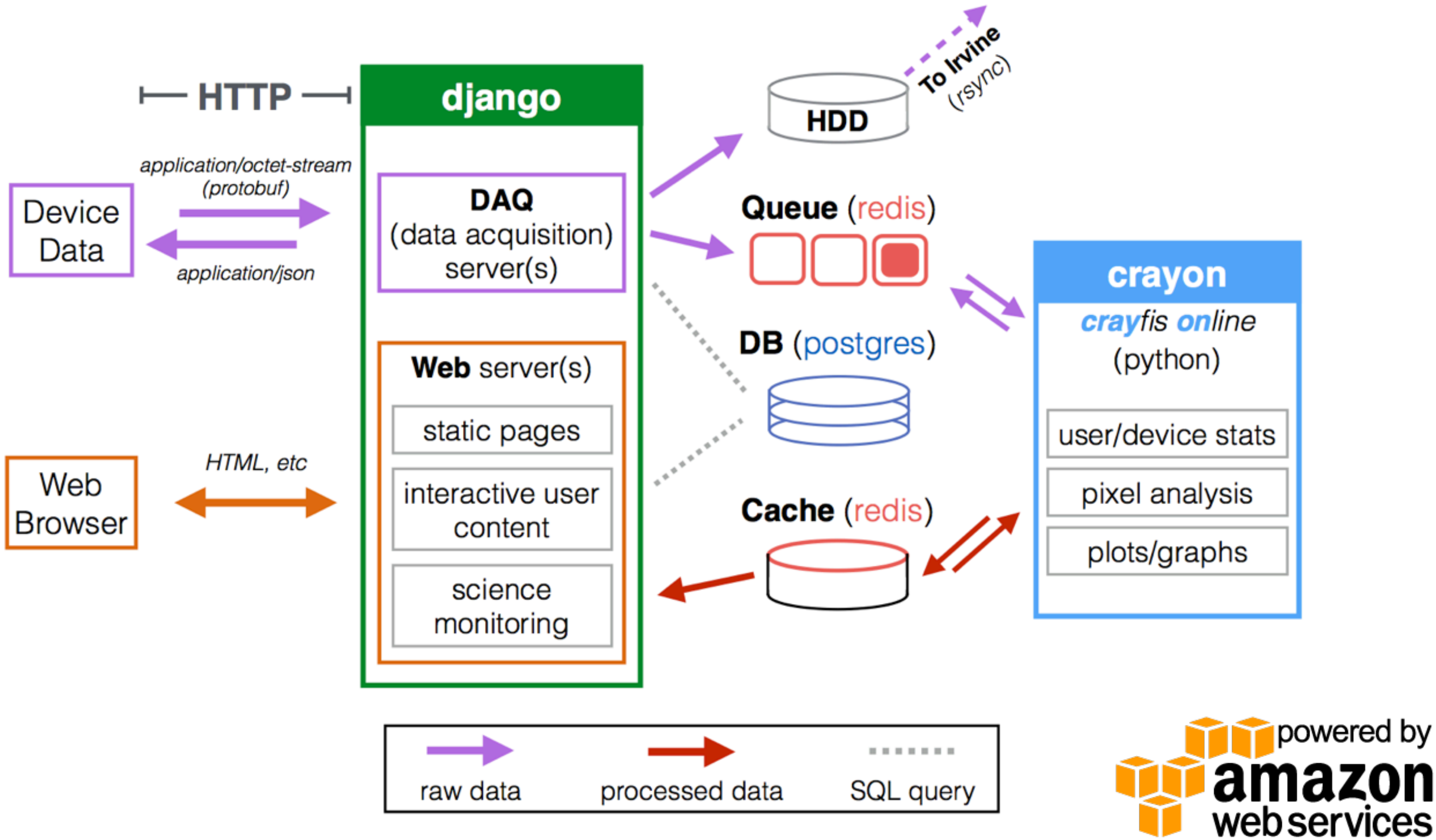
1M devices

10Mb/sec

5k simul. connections

$20k/month

DAQ



HTTP
Device Data
application/octet-stream (protobuf)
application/json
Web Browser
HTML, etc
django
DAQ (data acquisition) server(s)
Web server(s)
static pages
interactive user content
science monitoring
HDD
To Irvine (rsync)
Queue (redis)
DB (postgres)
Cache (redis)
crayon
crayfis online (python)
user/device stats
pixel analysis
plots/graphs
raw data
processed data
SQL query
powered by amazon web services

Science Challenges

Atmospherics

Shower dependence may depend on conditions

Energy calibration

Would prefer to avoid dependence on simulation.

Overburden

EM component may depend on amount of material overhead

User Challenges

<u>Make it exciting</u>

You can do astrophysics! (50k users in ~few days)

Leaderboard, prizes, public data, authorship!

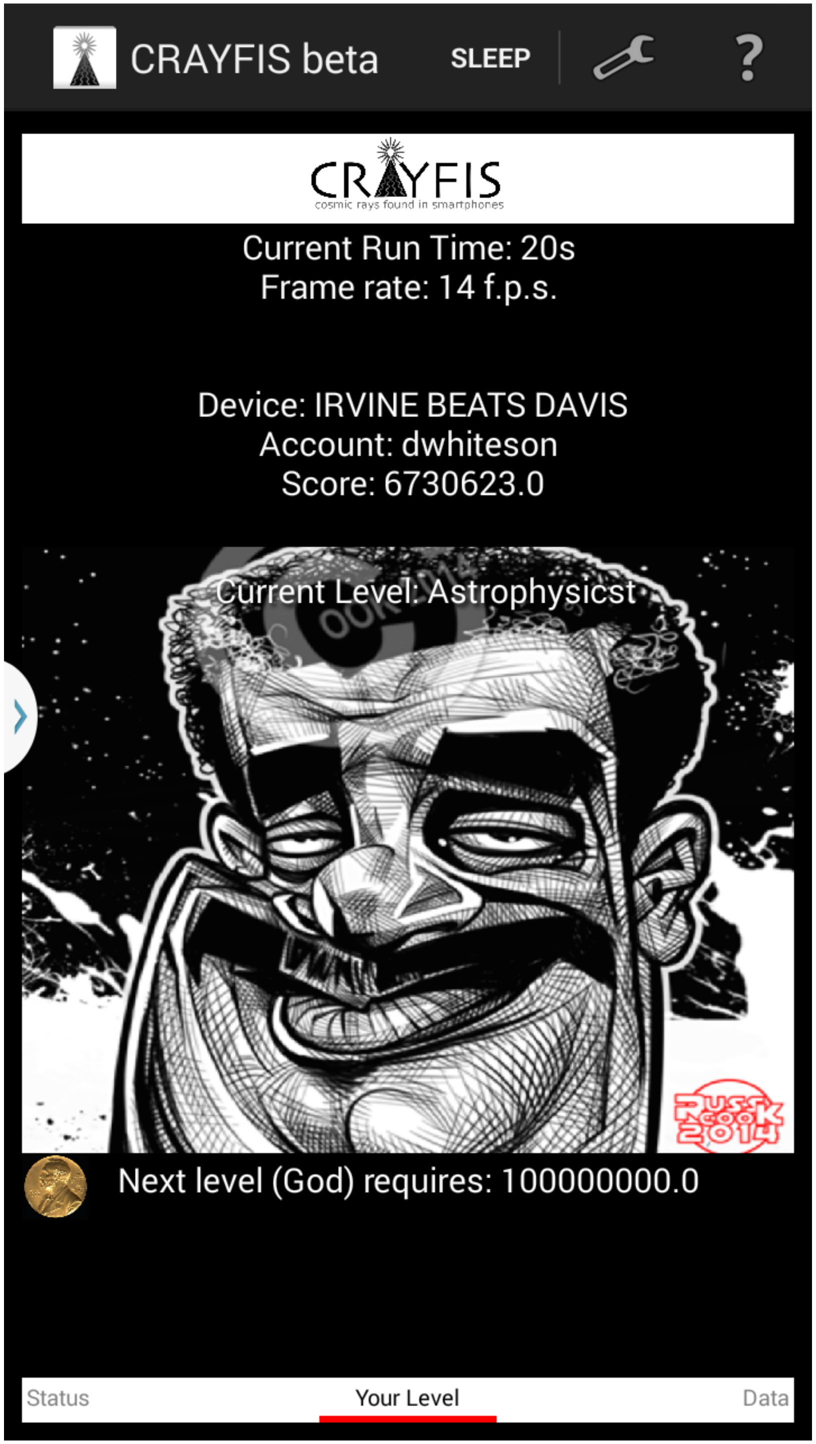
<u>Low barrier</u>

App is free, easy to install

Privacy measures

<u>Low maintenance</u>

App launches when device charging & not used



Motivate users

Provide levels

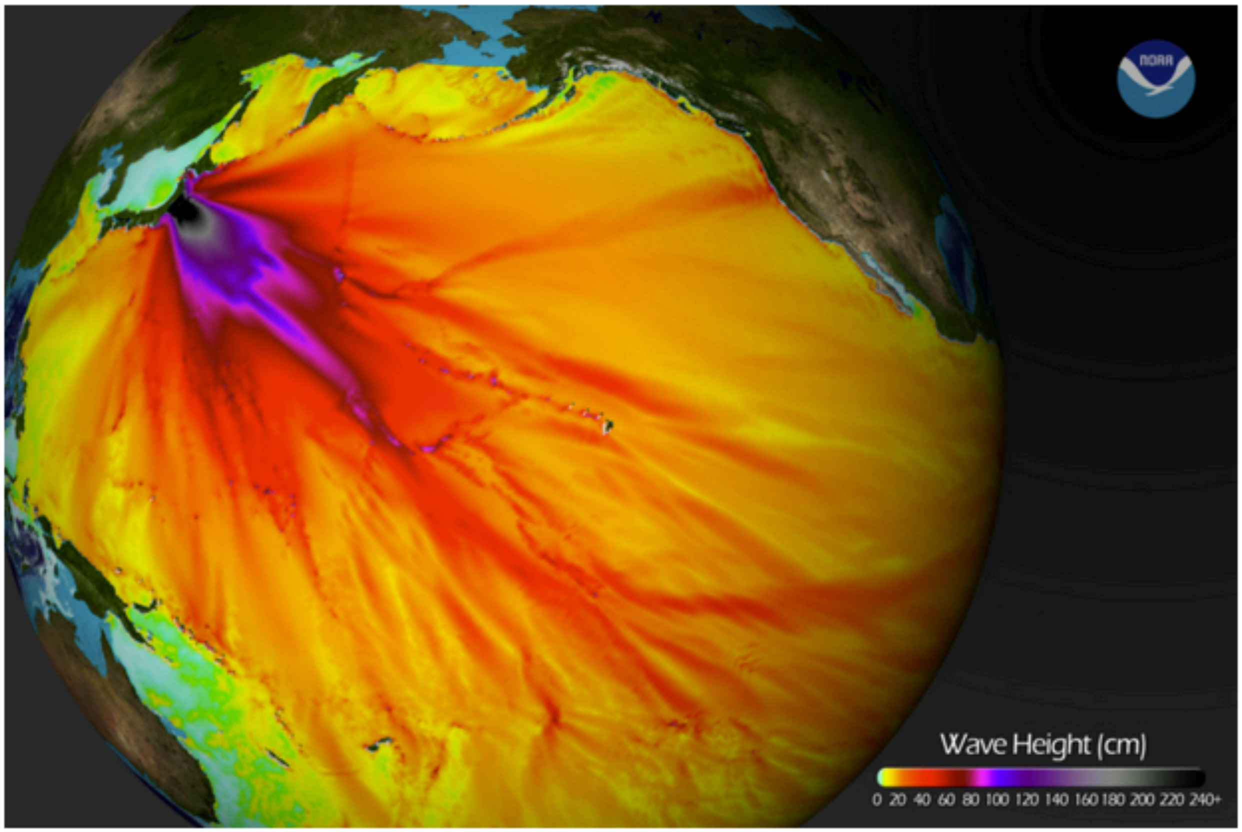
Occasional prizes

Post to fb/twitter

Radiation

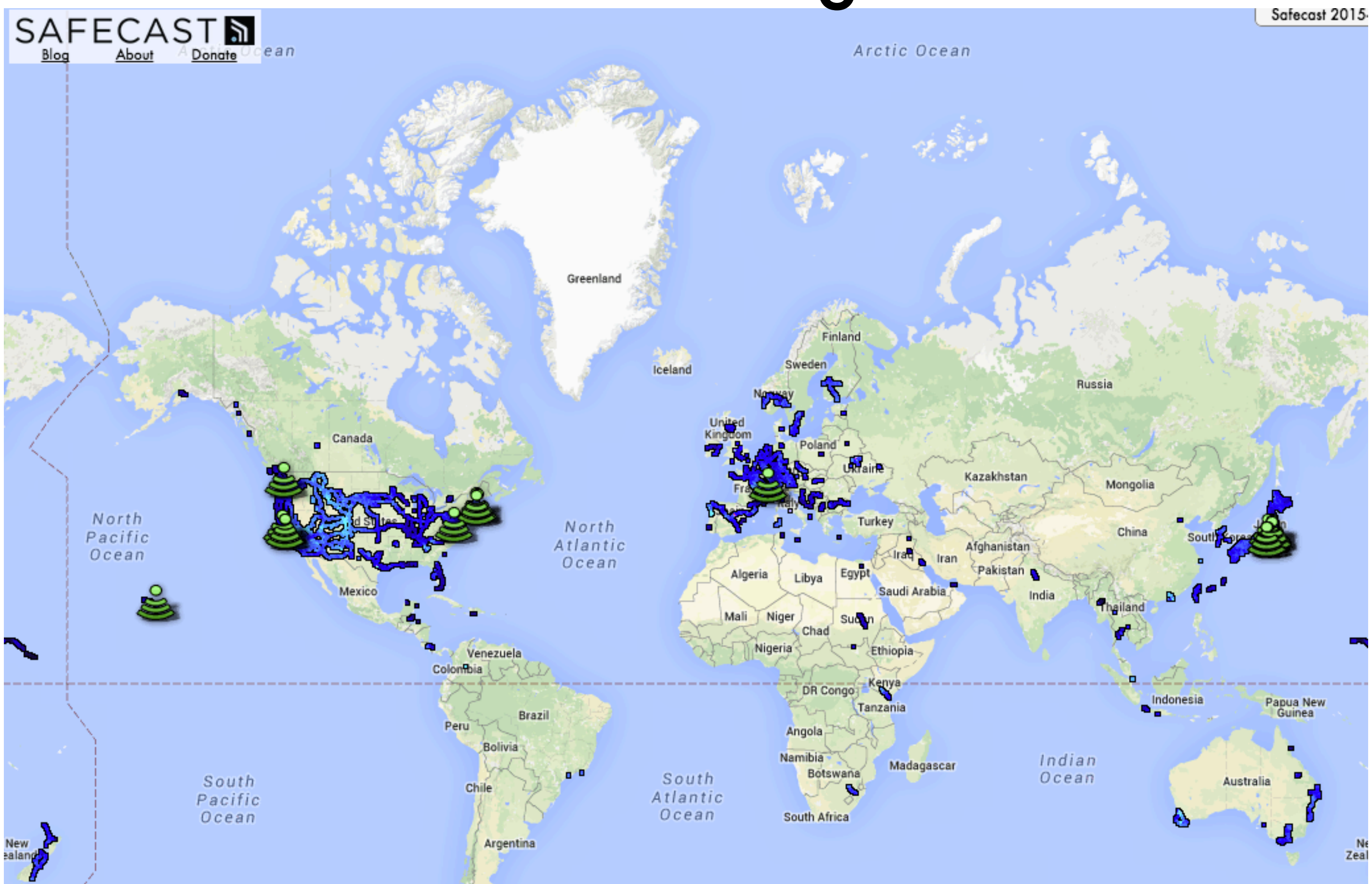
Motivation

FUKUSHIMA RADIATION TO HIT
WEST COAST



Existing maps?

safecast.org



Custom devices ($500), attached to vehicles.

Assume static radiation.

Radiation Applications

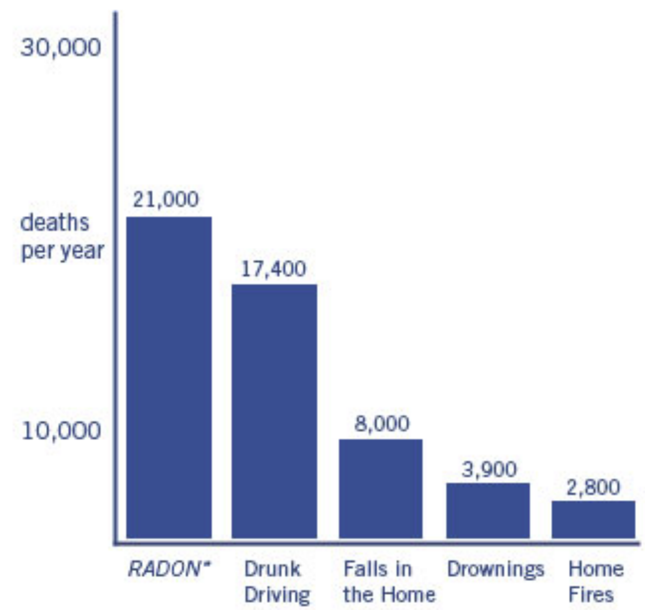
Local

Individual radiation alerts

Radon emissions

Global

Realtime worldwide map



http://www.epa.gov/radiation/docs/assessment/402-r-03-003.pdf

Timeline

Oct 13: posted paper
Oct 16: 25k users sign up for beta testing
Sep 1: 50k users sign up for beta testing

Beta testing

June 2015: wide release

Development

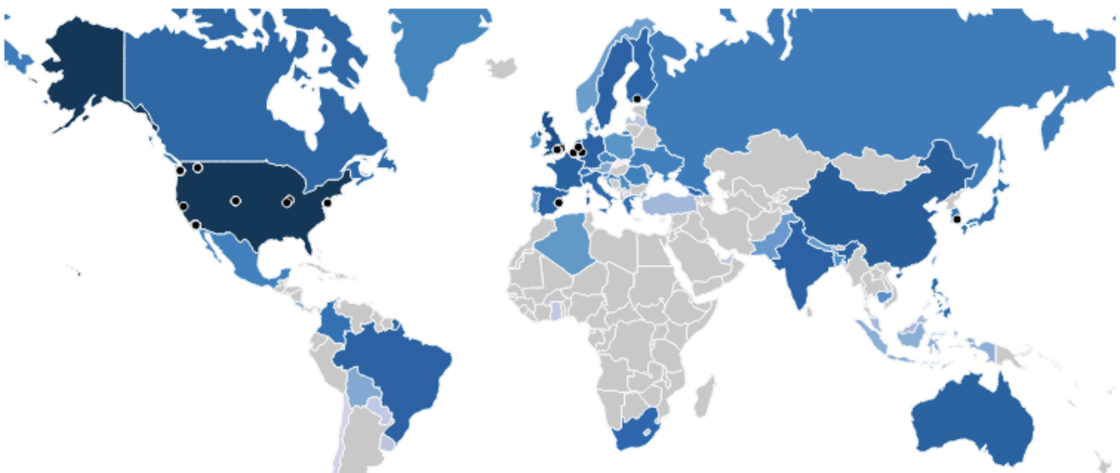
	Android	iOS	Chrome
1 '14	Devel		
	First app	Devel	
		First app	
	Alpha		
		Alpha	
1 '15			
	Beta		Devel
		Beta	First app
			Alpha
			Beta
6 '15	Wide	Wide	Wide

Live map

CRAYFIS
cosmic rays found in smartphones

Total Exposure	Unique Devices	Candidate Hits
6 years, 213 days, 19 hours	627	7,087,694

Network Map



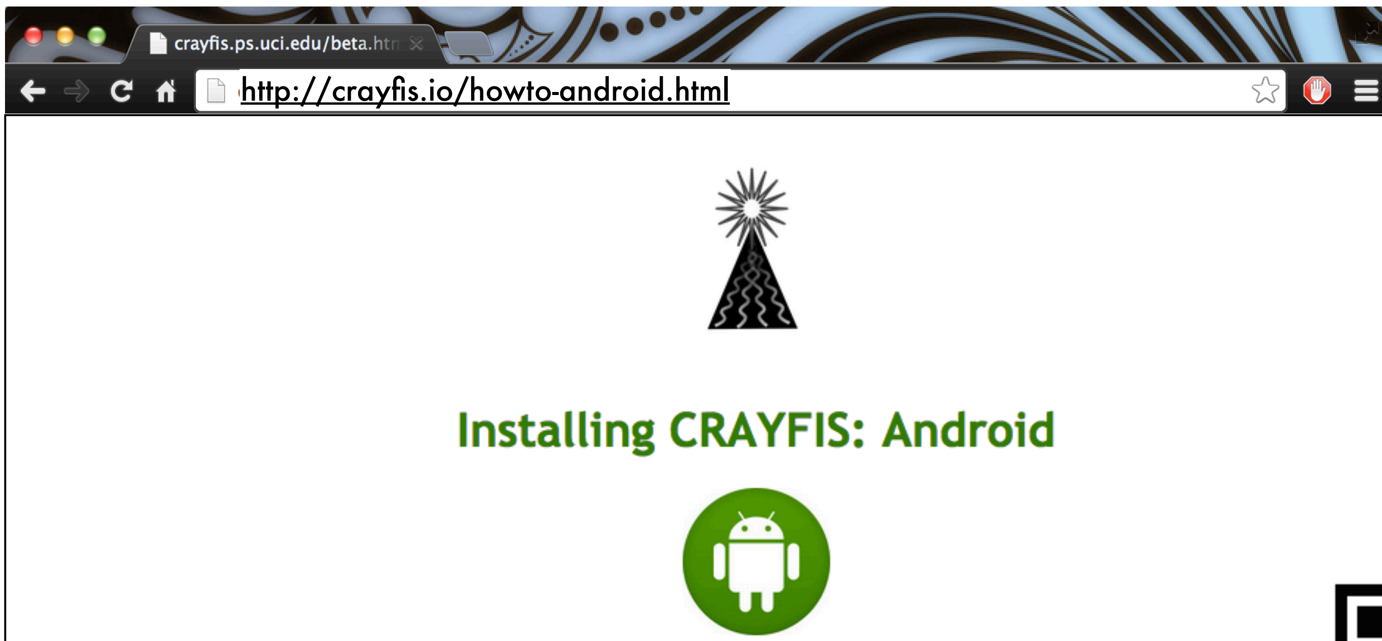
National Ranking

Rank	Country	Score
1	USA	48,255,080
2	NLD	8,065,897
3	GBR	7,582,600
4	BEL	4,647,677
5	CHN	2,224,118
6	AUS	1,981,232
7	FRA	1,797,232
8	IND	1,505,080
9	DEU	1,497,495
10	ESP	1,374,419

http://daq.crayfis.io/

Try it now!

http://crayfis.io/howto-android.html



Aiming for world records

<u>Highest energy CR observed.</u>

Target: 10^{21} eV

Current record: $3\ 10^{20}$ eV, Fly's Eye & Auger

<u>Most expensive experiment ever</u>

Target: $500B (already spent!)

Current record: ~$10B, LHC

<u>Longest author list</u>

Target: 1M

Current record: ~3000, ATLAS+CMS

Conclusions

Cosmic rays are an enduring mystery.

The existing network of mobile devices have unprecedented power to observe UHECR and other new phenomena.

Several technological and sociological challenges remain!

Fin

Calibration

Strategy

<u>Thermal noise</u>

Time-dependent (via temp)

<u>Cosmic ray muons</u>

Day/night variation

<u>Ambient radioactivity</u>

Location and time dependent.

<u>Hardware dependence</u>

Noise, sensor size & thickness

Strategy

Thermal noise

Time-dependent (via temp)

Cosmic ray muons

Day/night variation

Ambient radioactivity

Location and time dependent.

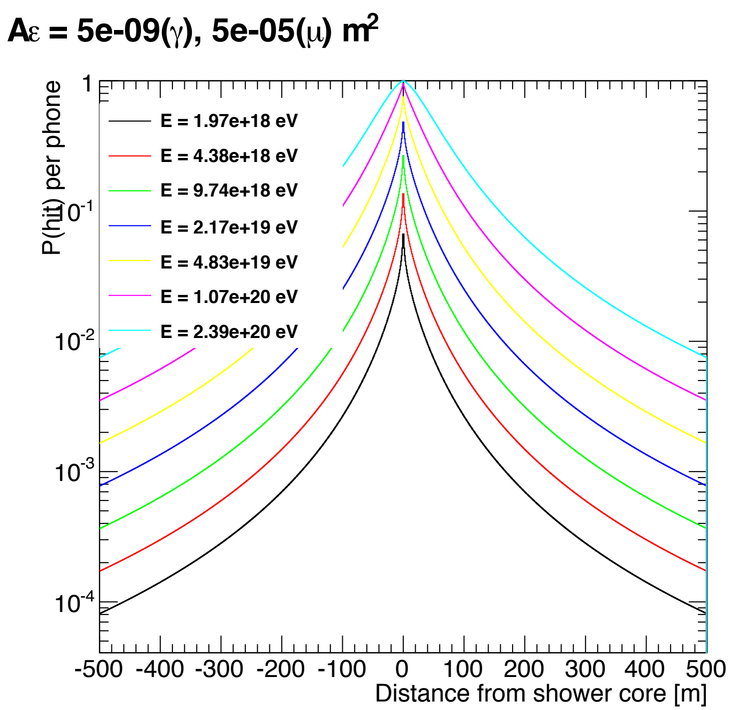
Hardware dependence

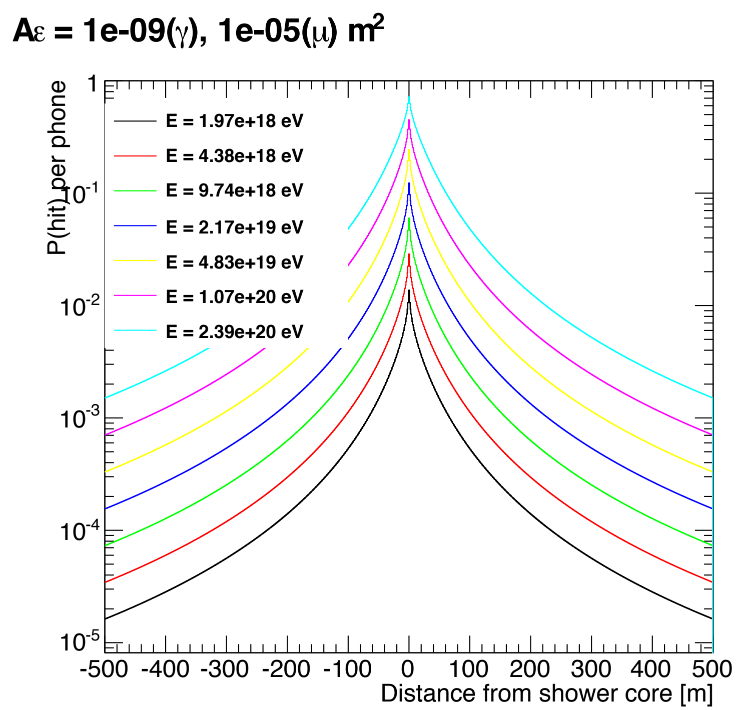
Noise, sensor size & thickness

Measure in situ

1) Can one count particles?
*For a a 10^20 eV shower the particle density falls below 10^6 /m2 at 250 m distance from the shower core. Thus, the detection probability of a single phone drops below A*epsilon * rho(gamma) ~ 2x10^-9 m2 * 10^6 /m2 = 2*10^-3 This is to be compared with 0.2 Hz background rate for 30 Hz camera frame picking => the noise probability per frame is 0.2/30 = 6*10^-3*
==> at ~250 m distance from the shower core, the noise probability per frame becomes higher than the shower particle detection probability, i.e. you collect mostly noise, rather than particles at larger distances.

Certainly our greatest sensitivity is at the shower core, falling rapidly at 100m from the core. Below you can see the probability for a phone to register a hit vs distance from the core in dx (assuming dy=0).





2) Can one trigger?
*A 5-phone coincidence within a 5 s window is said to give an expected background rate of 1% for photons. I don't know what that statement means (1% relative to what?), but in order to allow triggering a 10^20 eV shower with an efficiency close to one, all 5 phones should detect on average at least one particle. Thus, given the detection probability A*epsilon=2x10^-9 m2, one would at least need a particle density of 10^9 / m2. This density, however, is hardly reached even in a shower core at 10^20 eV. Thus, I don't see, how one would want to trigger on showers.*
Current air shower experiments reach 100% trigger threshold at much lower energies.

<u>Triggering</u>

The detector array has no global (multi-device) trigger.
Each device establishes a background level and report all hits above a threshold related to that background level. Coincidence will be established in off-line analysis.

Signal to noise

We acknowledge that the large number of phones will give a large number of spurious hits, and a non-negligible fraction will be coincident in time due to random coincidence. Since the posting of our paper, we have studied this in some detail and improved our simulations of noise-only showers.

@ Our studies indicate that the noise level falls rapidly above 10^19 eV. Including rate estimates for noise we find that reconstructed showers at 10^20 and 10^21 eV should have a small noise background.

@ We expect to be able to measure the noise profile very accurately using the data itself with random time-shifts added. This will capture the expected noise background of the distribution of phones with their real performance.

@ The signal to noise can be improved over simple coincidence counting using several methods:

a) Requiring that the spatial distribution be consistent with that expected from a UHECR. Specifically, this requires a large density near the core. Such a requirement reduces the rate of noise showers reconstructed at high apparent energies.

b) Requiring that the time distribution be consistent with a single shower; the profile of a shower will be a cluster in time with some width, while a noise shower will be flat in time

c) we hope to improve the timing resolution of the devices, which will reduce the noise levels

3) Can one reconstruct the energy, assuming one could trigger?
5000 phones/km2 = 1000 phones per 0.2 km2
Given the aforementioned particle densities and effective areas, one could indeed be able to detect some 10 particles, yielding a theoretical energy resolution similar to what is shown in Fig. 7 top.
Auger, for example reaches an energy resolution at 10^20 of ~ 10%, much better than the ones in Fig.7
Moreover, the phones would be at different location in buildings (sky-crapers) with the electromagnetic component mostly absorbed. This worsens the energy resolution easily to ~ 100%

Muons and Gammas

In our calculations, observations are dominated by the muonic component of the shower. The EM component is more difficult because the density at the sensor depends on the amount of material between the sensor and the shower core. At this point we have established that with sufficient phones CRAYFIS will have statistically sensitivity to UHECRs. We are greatly concerned with the systematic uncertainties related to the overburden and other factors that might vary the phone-to-phone efficiency and degrade our energy resolution. However, for any new detector, one first works to understand sensitivity and then develops calibrations and corrections. We have a number of ideas for controlling these systematics, including in-situ calibrations

However, even an energy resolution of 100% at 1e20 eV energies would be sufficient to establish observation above the GZK cutoff.

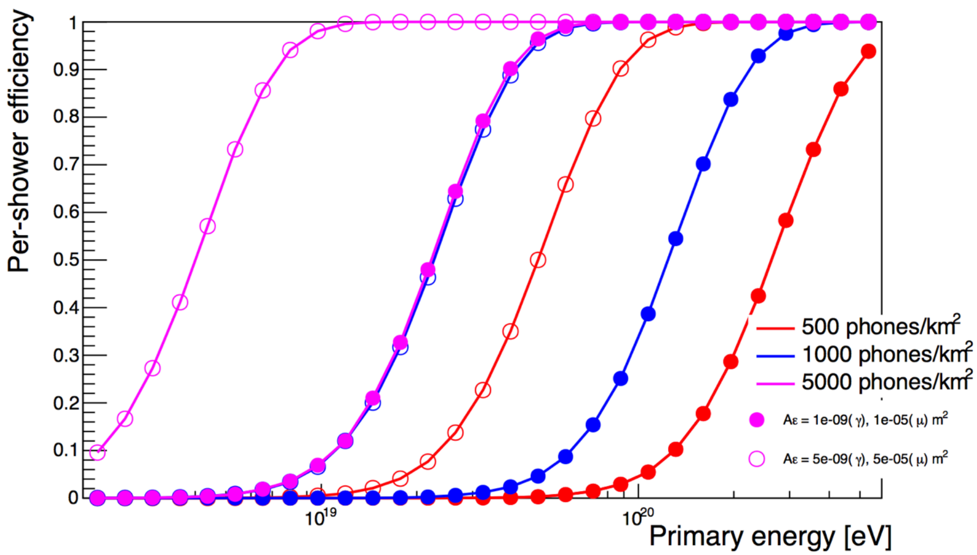
4) What could be the angular resolution?
Reaching angular resolution of 0.1 rad with a lever arm of 250 m on ground would require ~20 ns time resolution or better. How would one achieve this with 30 frames per second (delta-t = 33 milli-seconds)? Experiments like Auger have an angular resolution of 0.6 degree = 0.01 rad.

We do not use timing information to measure the incident angle.

Angular measurement.
We extract the incident angle from the eccentricity of the elipse (which gives theta), and the direction of the major axis (which gives phi) via a likelihood fit. No timing information is used.

As a result, we do not expect the angular resolution to be competitive with experiments such as Auger with access to precise timing information. However, with a potentially higher exposure, we hope to provide complementary information above the GZK cutoff.

5) Does one find 5000 phones per km2 easily?
Hongkong has a density of 6500 people/km2 and the total city area is 1100 km2.
On average, less than 1/3 of the smartphones could be operated, because they are connected to the charger only for a small fraction of time.



5k phones/km^2 is indeed a very large number.

However

a cluster of 500-1000 phones/km^2 reaches 50% efficiency for showers above 5e19-2e20 eV depending on the sensor sizes.

Note as well:

1) The number of mobile devices with cameras is growing rapidly
2) Camera sensor sizes are increasing in newer devices
3) We will expand soon to include laptops/desktops
4) Many people have > 1 device, including older devices not in use which could run 24 hr/day.

Efficiency Example:

From our simulations, here is an example:

Shower energy = 1.07e20 eV

N(gamma) = 4.6e11, N(mu) = 5.1e8

Ae(gamma) = 1e-9m^2 Ae(mu) = 1e-5m^2

Nphones = 1000   Mean Nhits = 4.1. Per shower eff (Nhits>=5) = 39%

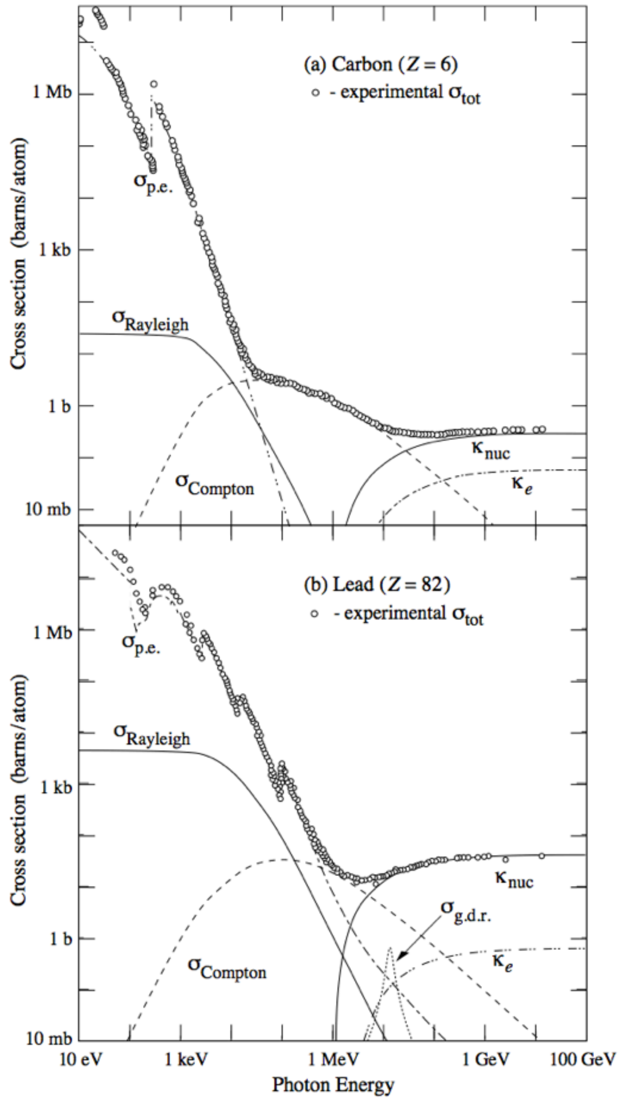


Figure 30.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [48]:

$\sigma_{\rm p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)

$\sigma_{\rm Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited

$\sigma_{\rm Compton}$ = Incoherent scattering (Compton scattering off an electron)

$\kappa_{\rm nuc}$ = Pair production, nuclear field

κ_e = Pair production, electron field

$\sigma_{\rm g.d.r.}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [49]. In these interactions, the target nucleus is broken up.

Original figures through the courtesy of John H. Hubbell (NIST).